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Aircraft Hangar Fire Suppression System Design Study

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13. ABSTRACT (*Maximum 200 words*)

The Navy and other military service branches within the Department of Defense are responsible for the fire protection of Department of Defense assets. These assets include high value military aircraft that are maintained and repaired in high bay aircraft hangars. These aircraft are essential elements of a strategic military force whose mission is unparalled by commercial aircraft. Previously, the Navy adopted fire protection standards embodied in industry standards for commercial aircraft protection. However, over time the Navy recognized the unique considerations that should be given to protecting vital assets, and that these considerations were not adequately addressed in the standards they were adopting.

The Navy identified a fundamental performance goal for its hangar fire protection systems. This goal was the installation of a reliable and easily maintained fire protection system, which prevents damage to the hangar structure and to the aircraft not directly involved in an initial spill fire ignition scenario. This resulted in a multi-year study to address all technical issues associated with meeting this goal.

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AIRCRAFT HANGAR FIRE SUPPRESSION SYSTEM DESIGN STUDY

1.0 BACKGROUND

The Navy and other military services within the U.S. Department of Defense (DoD) are responsible for providing fire protection systems capable of protecting DoD assets around the world. This includes the protection of high value military aircraft, which are maintained and repaired in high bay aircraft hangars. These aircraft are an essential element of a strategic military force whose mission is unparalleled by commercial aircraft. The Naval Facilities Engineering Command (NAVFAC) is responsible for the design, construction and maintenance of all shore-based facilities at U.S. Navy and Marine Corps bases worldwide.

Fire protection design criteria for Navy aircraft hangars have evolved over the years. Many of the existing hangars were built in the World War II era, and their fire protection consisted solely of overhead deluge water sprinkler systems activated by pneumatic rate-of-rise heat detectors. With the development of aqueous film-forming foam (AFFF), Navy design criteria were changed to include overhead AFFF deluge sprinkler systems, a variety of new detection systems, and in many cases, supplementary underwing foam monitor nozzles. These protection concepts are embodied within industry standards for protecting commercial aircraft hangars. Specifically, the National Fire Protection Association (NFPA) Standard on Aircraft Hangars (NFPA 409) is the recognized national consensus standard [1]. In essence, the protection concepts in NFPA 409 are recognized by DoD, even though there are unique considerations for protecting vital assets. These unique considerations are not necessarily addressed by NFPA 409, which is concerned primarily with property protection (i.e., protection of the hangar structure).

All DoD service branches have been plagued with false activations involving foam-water deluge sprinkler systems over aircraft with open cockpits. These false activations have been caused by numerous sources including: lightning strikes which introduced transient voltage spikes into the fire alarm system; water hammers in aging underground water distribution systems; accidental releases by maintenance personnel; deliberate acts of vandalism; accidental activation of manual pull stations; failure of pressure relief valves at pumping stations; roof water leakage into overhead heat detection systems and, false activation of fire detection systems. This prompted all branches of DoD to pursue alternative fire protection designs, which would provide the desired level of protection.

Alternative designs included the use of closed head AFFF overhead sprinkler systems, and greater reliance on low level monitor nozzle AFFF systems as the primary extinguishing component. Low level systems were originally designed to provide supplementary protection for the area shadowed from the overhead system by large wing areas. In pursuing these alternative designs, technical and operational issues and limitations of both existing and proposed new systems were identified:

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1. Thermally actuated systems may result in unacceptably high damage to assets prior to fire control/extinguishment, particularly in very high bay (i.e., high ceiling height) hangars;

2. While it is readily accepted that conventional hangar fire protection systems were not designed to extinguish a three-dimensional fire, fire protection engineers within DoD believed that AFFF extinguishing systems could be designed to control a spill fire and limit the area of fire involvement to only those aircraft intimate with the initial ignition source;

3. Different aviation fuels are now being commonly used, e.g., JP-5 and JP-8 are now the predominant fuels, compared to the lower flash point JP-4 previously used;

4. Low level AFFF monitor nozzle systems are:

    a. Relatively inefficient in terms of pattern distribution;

    b. Unreliable;

    c. Susceptible to blockage by equipment; and

    d. Commonly found out-of-service in the field;

5. Any new AFFF low level nozzle should be designed for minimal overspray, and should not be significantly impacted by water discharge from any water only protection system;

6. Optical detectors are:

    a. Prone to false alarms;

    b. Currently tested/listed/approved using fuels that are not typically used in aviation; and,

    c. Subjected to few if any false alarm nuisance sources in currently recognized approval standards.

NAVFAC initiated a multi-year study to address these technical issues. A fundamental performance goal was established: a reliable and easily maintained fire protection system, which prevents damage to aircraft not directly involved in an initial spill fire ignition scenario, and the hangar structure, should be installed. NAVFAC developed a concept to meet this goal. This concept includes the:

1. Use of low level AFFF deluge nozzles, having minimal overspray, to control/extinguish liquid fuel pool spill fires;

2. Operation of the low level AFFF system using improved optical detectors designed to:

   a. Be highly immune to false alarms; and,

   b. Rapidly detect JP-5 fuel spill fires.

3. Installation of a quick responding, closed head, wet pipe sprinkler system in the hangar ceiling and,

4. Implementation of lessons learned from all DoD hangar design experience in a comprehensive new, improved design.

Most of the R&D associated with the developmental process has been completed [2-7]. The objective of this design study is to: review the rationale and basis for current designs and protection criteria; identify the issues and concerns with existing and proposed new designs; review the R&D performed to address technical issues and outline and document a recommended design methodology which can be adopted for improved hangar fire protection designs.

2.0 FACILITY DESCRIPTION

The size of military hangars vary greatly both in floor plan area and roof height. However, a modular design is encouraged by NAVFAC to allow for flexibility and economical expansion using modified internal rearrangement and/or additional maintenance modules. A DoD handbook, Aircraft Maintenance Facilities (MIL-HDBK-1028/1C) [8] sets out guidelines covering the design requirements for Aircraft Maintenance Hangars. Two types of modular maintenance hangars are specified in the guide: Type I and Type II.

A Type I hangar (Fig. 1 and Fig. 2) is principally designed for carrier aircraft, but is adaptable to meet requirements for rotary wing and various types of smaller aircraft. Associated office/shops areas are designed for a typical strike fighter squadron, two carrier airborne early warning squadrons, or a helicopter antisubmarine warfare squadron. A Type II hangar is principally designed for a patrol squadron but is adaptable for the larger aerial refueling and transport aircraft. Associated office/shops areas are designed to accommodate a typical marine aerial refueling and transport squadron or Navy patrol squadron.

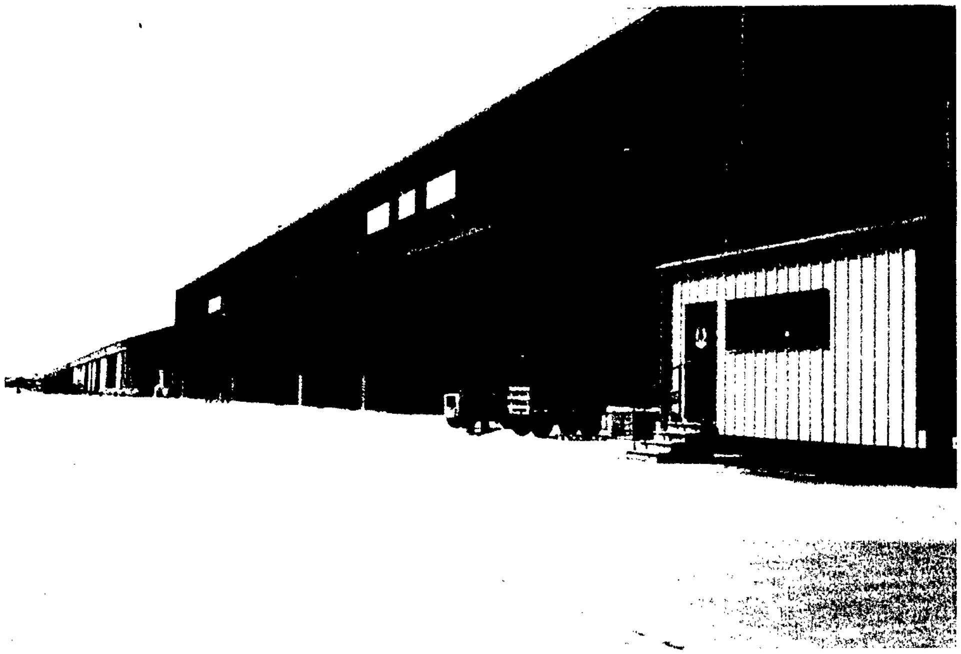

Fig. 1 . Type I Hangars Consisting of Double Modules

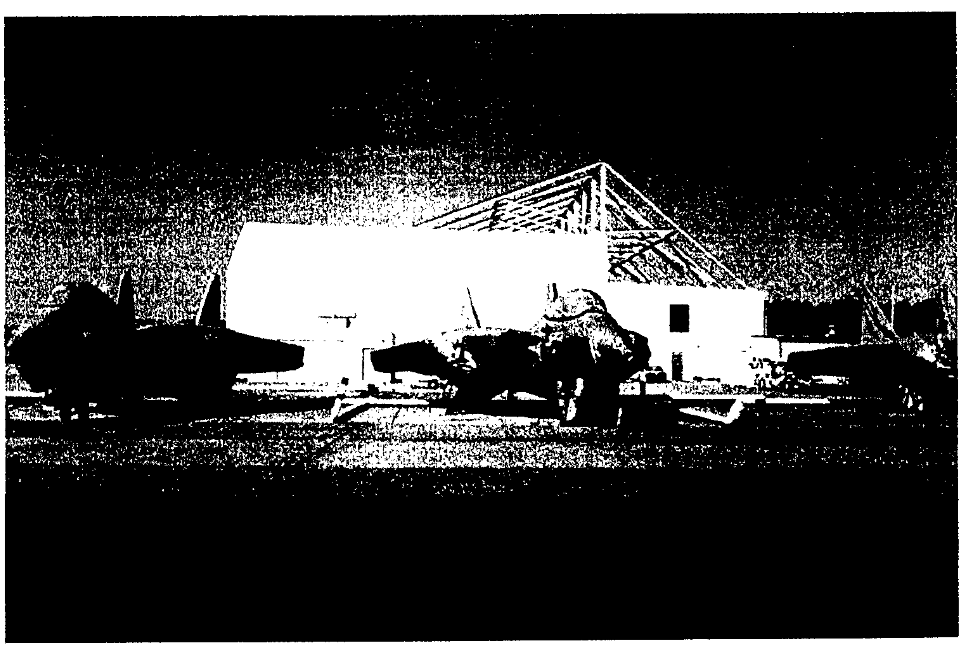

Fig. 2 . Type I Hangar with Cantilevered Roof

2.1 Construction of Military Hangars

2.1.1 Existing Hangars

There are many styles of hangars currently in use on Navy bases. However, there are a number of features that are predominant in some older style hangars. These include:

1. Hangar doors at opposite ends of the hangar creating a drive through geometry (see Fig. 3),

2. Vaulted roofs (see Fig. 3),

3. Inadequate drainage often consisting of only a main drain at the hangar door with a sloped floor and no internal drains, and

4. Typically a non-combustible (steel) roof (however some older hangars are of timber construction).

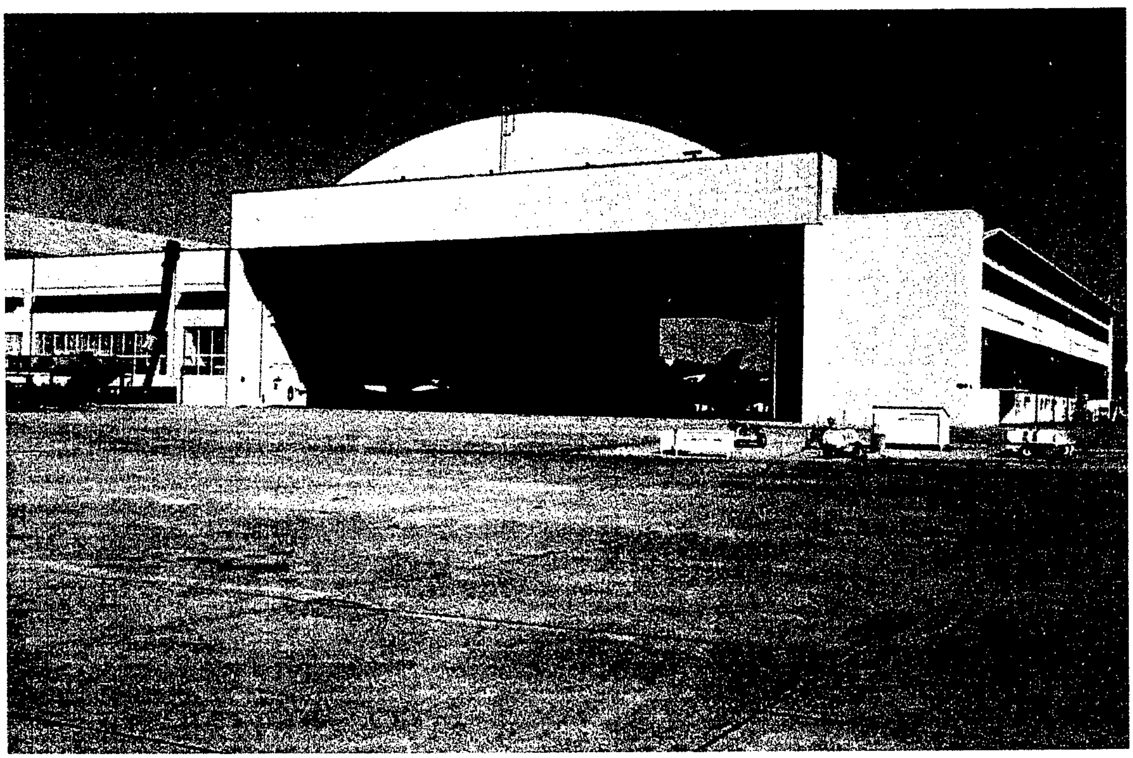

Fig. 3 . Older Style Hangar with Drive-Through Geometry and a Vaulted Roof

2.1.2 New Hangars

MIL-HDBK-1028/1C sets out architectural and engineering design guidelines for hangars. Table 1 contains a summary of some of the basic module requirements.

Table 1. Type I and II Maintenance Hangar Requirements

Guideline Criteria	Type I	Type II
Hangar Bay Area	30.5 x 58.5 m (100 x 192 ft) 1,784.5 m^2 (19,200 ft^2)	35 x 73 m (115 x 240 ft) 2,555 m^2 (27,600 ft^2)
Minimum Ceiling Height	7.6 m (25 ft)	11.6 m (38 ft)
Roof System	Column free front cantilevered roof structure – approval for alternative required.	
Floor Drainage	To meet the requirements of NFPA 409.	
Hangar Doors	Single set of a series of horizontally sliding leaves located on a longer side of the module.	

2.2 Fire Protection Requirements

Current design requirements for fire protection systems in Navy hangars are outlined in three documents: MIL-HDBK-1028/1C; MIL-HDBK-1008C, Fire Protection for Facilities Engineering, Design and Construction [9]; and NFPA 409. The requirements of the military handbooks are noted to be used as guidance only.

Protection criteria in NFPA 409 split hangars into one of three categories based on the hangar door height or the aircraft tail height (when there are provisions for housing aircraft with tail heights greater than the door height). The maximum area of a single hangar bay and the construction type are also factors (see Table 2). The rationale for these categories is that the

Table 2. NFPA 409 Aircraft Hangar Design Categories

Hangar Categories	Criteria
Group I	(a) Door height over 8.5 m (28 ft); or (b) Single fire area > 3,716 m^2 (40,000 ft^2); or (c) Provision for housing aircraft with a tail height > 8.5 m (28 ft).
Group II	(a) Door height less than 8.5 m (28 ft); and (b) A floor area between 464.5 and 3,716 m^2 (5,000 and 40,000 ft^2) depending on construction Type.
Group III	(a) Door height less than 8.5 m (28 ft); and (b) A floor area between 464.5 and 2,787 m^2 (5,000 and 30,000 ft^2) depending on construction Type.

door/tail height will restrict the size of aircraft that may enter the hangar. Limits on the area of a single hangar bay size will restrict the number of aircraft in the hangar. Inherent in these design criteria is that the taller the tail height or the more aircraft in the hangar, the more fuel is

potentially in the hangar and therefore the greater the fire risk. NAVFAC specifications for Type I and II maintenance hangars result in all new military maintenance hangars being categorized as Group I hangars.

For each of the hangar category groups, NFPA 409 lists different fire protection features. Typically a Group I hangar has the most stringent fire protection requirements.

3.0 HISTORICAL BASIS OF HANGAR FIRE PROTECTION

3.1 Design Objectives

The two objectives of aircraft hangar protection are: (1) protection of aircraft; and (2) prevention of damage to the hangar structure, particularly to prevent collapse of the roof structure, which is typically, unprotected roof steel. DoD has historically referenced NFPA 409, with modifications. The scope of NFPA 409 is limited to the minimum requirements for the proper construction and protection of aircraft hangars from fires. The purpose of the standard is to "...provide a reasonable degree of protection from fire for life and property in aircraft hangars..." The emphasis of the protection criteria is on the hangar structure. Both the Navy [9] and Air Force [10] modify NFPA 409 protection criteria to address protection of vital assets. However, the majority of the requirements in NFPA 409 are currently adopted by reference by DoD.

Protection criteria in NFPA 409 are based on deluge-type sprinkler systems with open head nozzles, which are activated by thermal detection systems. Prior to the development of foam, water deluge systems were used. The original foam-water sprinkler systems used protein foam. With the development of AFFF, research was performed to determine appropriate application rates and types of discharge devices. The research work, performed primarily by Factory Mutual Research Corporation (FMRC), provides the basis for most current aircraft protection criteria. The protection criteria were developed based on relatively large spill fire scenarios. A key measure of performance was steel roof temperature, which is used to predict imminent roof collapse. A detailed review of the history of hangar protection criteria can be found in Reference [11].

3.2 Overhead Sprinkler Protection

Before the advent of foam, hangars were protected by conventional spray sprinklers using water. Water deluge systems having discharge rates on the order of 10.4 Lpm/m^2 (0.25 gpm/ft^2) were used in conjunction with sloped floors and drains to protect aircraft. Even with these systems, activated by thermal detection systems, burn-through protection of aircraft fuselages (e.g., within 1 minute) could not be assured. Ceiling temperatures in an 18.3 m (60 ft) high space on the order of 427 to 816 °C (800 to 1500 °F) were recorded for fuel spill fires where this

protection was provided. For a 121 m^2 (1,300 ft^2) JP-4 fuel fire, 927 °C (1,700 °F) ceiling temperatures were recorded within 30 seconds of ignition prior to deluge system discharge [11].

Protein foam systems, discharging at a rate of 8.2 Lpm/m^2 (0.20 gpm/ft^2), were an improvement on the water systems. Air-aspirating sprinklers were required to make effective protein foam. Because of the high centerline velocities of a pool fire plume, the foam flow through the perimeter toward the center of the fire was thought to be the dominant suppression mechanism [12].

With the development of AFFF, FMRC conducted a series of tests for the U.S. military to establish appropriate design parameters. In a series of baseline comparison tests, FMRC compared AFFF with protein foam. The tests consisted of 83.6 m^2 (900 ft^2) JP-4 pool fires in an 18.3 m (60 ft) high space. Air-aspirating, standard upright and old style upright sprinklers were evaluated at application rates of 4.1 to 8.2 Lpm/m^2 (0.10 to 0.20 gpm/ft^2). In one test, a low level turret nozzle discharging AFFF was used in conjunction with sprinklers discharging water. Table 3 summarizes the results of the AFFF tests. A comparison of Tests 4 and 5 with Test 3 indicates improved results from the use of standard sprinklers compared to foam-water

Table 3. Hangar Deluge System Tests by Factory Mutual Research Corporation [12]

Test Conditions	Test No. 2	Test No. 3	Test No.4	Test No.5	Test No. 6	Test No. 7 (turret nozzle)
Type of Head	Foam-water	Foam-water	Standard	Standard	Standard	Old-style Sprinkler
Spacing {$m^2 head^{-1}$ ($ft^2 head^{-1}$)}	7.4 (80)	9.3 (100)	12.1 (130)	12.1 (130)	9.3 (100)	9.3 (100)
Application Rate {Lpm/m^2 (gpm/ft^2)}	8.2 (0.20)	6.6 (0.16)	6.6 (0.16)	6.6 (0.16)	5.2 to 4.4 (0.125 to 0.105)	6.6 (0.16) (water system)
End Head Pressure {kPa (psi)}	193 (28)	193 (28)	97 (14)	97 (14)	35 (5)	55 (8) (water system)
25% Drainage Time (min)	2.5	2.1	0.5-0.8	1.0-1.3	0.5-0.7	No data recorded
50% Drainage Time (min)	5.0	4.4	1.3-1.8	1.8-2.3	1.2-1.6	No data recorded
Expansion Ratio	4.3:1	3.4:1	2.2:1	2.3:1	2.2:1	12:1
Extinguishment Time (min:sec)	2:22	2:15	1:45	1:25	3:05	≈0:33

sprinklers. At application rates of 6.6 Lpm/m^2 (0.16 gpm/ft^2), the standard sprinklers were 1.3 to 1.6 times as effective in achieving extinguishment compared to air-aspiration foam-water sprinklers. At an application rate of 8.2 Lpm/m^2 (0.20 gpm/ft^2) the extinguishment times with AFFF discharged from foam-water sprinklers were comparable to results from protein foam tests.

AFFF discharged from foam-water sprinklers were comparable to results from protein foam tests. Rapid suppression with the turret nozzle (at 8.3 Lpm/m^2 (0.22 gpm/ft^2)) combined with an overhead water system was demonstrated in Test 7. No adverse effects were evident from the water discharge from the overhead sprinklers after the foam ran out.

The practical significance of AFFF discharge through non-air-aspirating sprinklers was demonstrated by Breen et al. [13]. Air-aspirating sprinklers require 207 kPa (30 psi) nozzle pressure to be effective. Standard sprinklers can discharge effective AFFF solution at pressures as low as 69 kPa (10 psi). This had important retrofit considerations where foam proportioning system losses could be made up through reduced sprinkler pressures.

Additional tests were conducted with closed head sprinklers in an 18.3 m (60 ft) high hangar [14]. Potential cost benefits would have resulted from reduced hardware costs and unwanted discharges from deluge systems. These tests demonstrated that this concept was not feasible for the hangar scenario because of the large number of sprinklers that opened during the 83.6 m^2 (900 ft^2) fire tests.

3.3 Low Level Application of AFFF{tc \l2 "3.3 Low Level Application of AFFF}

With the increase in wingspan areas of large aircraft, it was recognized that significant damage could occur before extinguishments of the pool fire underneath the wing. Using overhead sprinklers only, FMRC demonstrated the time required for the foam to spread and extinguish fires (see Table 3). The concept of low level application of foam, using monitor or turret nozzles, was developed to reduce extinguishments time where shielded fires may occur. This concept was later extended to include side-mounted nozzles and discharge outlets, and flush mounted nozzles installed in a floor or deck.

These systems are effective because AFFF solution droplets do not have to penetrate the fire plume. They also typically deliver, at spot locations, high densities of foam. This allows the foam to gain a "bite" or toehold on the fire. NFPA 409 criterion of 4.1 Lpm/m^2 (0.10 gpm/ft^2) for low level applications is based on a fire control time of 30 seconds and extinguishments in 60 seconds. This criterion is based on low level turret nozzle tests conducted by FMRC [13].

Table 4 summarizes fire test data for low level application of AFFF. As seen, control and extinguishments times are quite rapid. NFPA 409 criteria of 4.1 Lpm/m^2 (0.10 gpm/ft^2) for supplementary low level applications is based on a fire control time of 30 seconds and extinguishments in 60 seconds. Data indicated that a JP-5 pool fire can be controlled in 60-90 seconds and extinguished in two minutes when an application rate of 2.5 Lpm/m^2 (0.06 gpm/ft^2) is used. The system can be effective at rates as low as 1.6 Lpm/m^2 (0.04 gpm/ft^2). For lower flashpoint fuels (e.g., Avgas), control time increases. Control and extinguishments time can be

Table 4. Fire Test Data for Low Level Application of AFFF

Reference	Test No.	Test Area M^2 (ft^2)	Fuel	Nozzle	Nozzle k Factor (gal/$psi^{0.5}$)	Maximum Spray Height[1] m (ft)	Spray Diameter[1] m (ft)	Nominal Application Rate Lpm/m^2 (gpm/ft^2)	Control and Extinguishment Times
FM 1975[16]	3	83.6 (900)	JP-4	Turret Nozzle (monitor)	50.3	50° arc, 8 s cycle time, 15° angle of elevation, 25.9 m (85 ft) from the center of the test pool		4.1 (0.10)	90% in 10-15 s 100% in 35-40 s
	4	83.6 (900)	JP-4	Turret Nozzle (monitor)	50.3	50° arc, 8 s cycle time, 15° angle of elevation, 25.9 m (85 ft) from the center of the test pool		4.1 (0.10)	90% in 1 min 30 s[2] 100% in ≈2 min
	6	83.6 (900)	JP-4	Turret Nozzle (monitor)	50.3	50° arc, 8 s cycle time, 15° angle of elevation, 25.9 m (85 ft) from the center of the test pool		4.1 (0.10)	90% in 20 s 100% is 25 s
FM 1973[12]	7	83.6 (900)	JP-4	Overhead OSS[3] + Turret Nozzle	5.6 5.0	NA	NA	6.5 (0.16)[4] + 9.0 (0.22) 9.5 (0.38)	Control in 17 s[4] 100% in 33 s
Australia[17]	1	78.5 (846)	Aviation Kerosene	P10 pop-up	4.1	0.8 (2.6)	4.3 (14.1)	5.5 (0.13)	95% in 30 s
	2	78.5 (846)	Aviation Kerosene	W-1 pop-up	3.6	1.5 (4.9)	3.3 (10.8)	4.9 (0.12)	≈90% in 25 s[5]
	3	78.5 (846)	Aviation Kerosene	P10	4.1	0.8 (2.6)	3.3 (10.8)	5.5 (0.13)	98% in 30 s
NWC Phase III 1972[18]	5	697 (7500)	JP-5	Type S Flush Deck	5.5	1.8 (6)	12.2 (40)	1.6 (0.04)	50% in 30 s 90% in 60 s
	11	697 (7500)	JP-5	Type S Flush Deck	5.5	1.8 (6)	12.2 (40)	2.4 (0.06)	70% in 30 s 95% in 60 s
	9	697 (7500)	Avgas	Type S Flush Deck + Deck Edge	5.5 114 Lpm (30 gpm)	1.8 (6)	12.2 (40)	2.4 (0.06) + 1.6 (0.04) 4.1 (0.10)	15% in 30 s 50% in 60 s
	15	697 (7500)	Avgas	Type S Flush Deck + Deck Edge	5.5 114 Lpm (30 gpm)	1.8 (6)	12.2 (40)	2.4 (0.06) + 1.6 (0.04) 4.9 (0.12)	40% in 30 s 70% in 60 s

Table 4. Fire Test Data for Low Level Application of AFFF (concluded)

Reference	Test No.	Test Area m^2 (ft^2)	Fuel	Nozzle	Nozzle k Factor (gal/$psi^{0.5}$)	Maximum Spray Height[1] m (ft)	Spray Diameter[1] m (ft)	Nominal Application Rate Lpm/m^2 (gpm/ft^2)	Control and Extinguishment Times
NWC Pop-up 1985[19]	10 & 10R	372 (4000)	JP-5	Type SB Flush Deck	5.1	1.8 (6)	9.1-12.2 (30-40)	2.4 (0.06)	60-90 s for 90% control; 99% in 2 min
	5, 5R & 5R1	372 (4000)	JP-5	Bete Pop-up	5.5	1.8 (6)	9.8 (32)	2.4 (0.06)	60-90 s for 90% control; 99% in ≈2 min
NWC Weapons Staging Area 1986[20]	I8	48.3 (520)	JP-5	Overhead Side-mounted Spray Nozzles	1.9	NA	NA	8.6 (0.21)	90% in 15 s 99% in 52 s 100% in 57 s
	I11	48.3 (520)	JP-5	Overhead Side-mounted Spray Nozzles	1.9	NA	NA	21.6 (0.53)	90% in 8 s 99% in 15 s 100% in 27 s
	II6[6]	66.9 (720)	JP-5	Low Level Fan	4.7	NA	NA	11.8 (0.29)	90% in 24 s 99% in 52 s 100% in 79 s
	II12[6]	66.9 (720)	JP-5	Low Level Fan	4.7	NA	NA	20.4 (0.50)	90% in 9 s 99% in 16 s

NOTES:
1 Spray height and diameter at the pressure/flow used in the test.
2 An unplanned 10 psi pressure drop in Test 4 caused a 4.6 m (15 ft) reduction in nozzle range resulting in 90% control and extinguishment times 3-4 times those observed in Tests 3 and 6.
3 No wing obstruction over fire test area.
4 The overhead deluge system discharging ordinary water was accidentally activated 12 seconds later than the turret nozzle (5 seconds before control was attained). The contribution if any, of the overhead deluge system toward complete extinguishment was judged to be quite small compared to the turret nozzle.
5 Wind affected results.
6 Deck pool fire area was obstructed with simulated weapons carts reduced by increasing the

reduced by increasing the application rates on JP-5 fuel fires. Based on these results, the U.S. Navy adopted an AFFF application rate of 2.5 Lpm/m^2 (0.06 gpm/ft^2) for protecting aircraft carrier flight decks [15].

While it may help control a three dimensional (spill) fire, a low level system cannot be assumed to totally suppress a running fuel fire. However, the pool fire resulting from a spill should be extinguished by a flush deck or low level system.

Obstructions, such as parked vehicles, may block low level nozzles. Testing for a flight deck weapons staging area showed that a side-mounted low level system could be effective even when nozzles are obstructed [20]. In these tests, five of 12 deck edge nozzles were obstructed to simulate fires obstructing edge-mounted nozzles. Even with 40 percent nozzle obstructions, the fire was controlled and extinguished in less than one minute (compared to 15-30 seconds when unobstructed).

3.4 Draft Curtains

Recent research has shown that draft curtains are effective at reducing the activation times of ceiling level thermal detectors. This is achieved by containing the area over which the hot gases can spread and mix. Decreasing the mixed hot gas volume maintains an increased hot layer temperature leading to faster activation of detectors. Although prior to the 1960s draft curtains were mandatory, the requirement for their inclusion in high bay hangar spaces was removed from NFPA 409 because there was no large scale experimental data justifying their effectiveness. This requirement was replaced with the current requirement that draft curtains be provided in large area hangars where deluge sprinkler systems are zoned for non-simultaneous operation. As the activation of any detector in a hangar bay will operate the entire associated deluge system, it is important to limit the spread of heat to only those systems immediately above or adjacent to the fire. In order to achieve this, draft curtains are required to be installed between deluge systems in hangars where not all systems are automatically operated when a detector is activated. This usually occurs in hangars having a very large floor area and/or limited water supply.

3.5 Drainage

NFPA 409 requires the inclusion of drainage systems that have sufficient capacity to prevent build up of flammable liquids and water. These systems must be designed to handle the discharge from all fire protection systems and hose streams. Drainage has been included as a requirement for hangars constructed to NFPA 409 since the 1960s. The aim of drainage systems is twofold: first, to remove any flammable liquids from the hangar as rapidly as possible; and, second, to limit the size of any pool of flammable liquid that may be generated from a spill. Both of these approaches reduce the hazard that flammable liquid spill fires present to the hangar structure.

4.0 CURRENT NAVFAC CRITERIA AND PROPOSED STRATEGY

Current protection criteria for Navy hangars is contained in Military Handbook 1008C (MIL-HDBK-1008C), Fire Protection for Facilities Engineering, Design Construction [9]. The criteria were developed based on the FMRC test data, NFPA 409, and the recognition of numerous false discharges from existing systems. MIL-HDBK-1008C requires new and renovated aircraft hangars to comply with NFPA 409, except as modified. These modifications include the specification of closed head AFFF sprinklers discharging 6.6 Lpm/m^2 (0.16 gpm/ft^2) from the ceiling. NFPA 409 currently does not recognize the use of closed head sprinklers in Group I hangars. Supplementary protection is required for hangars, which can accommodate large or multiple high value aircraft. This protection must be automatic low level (underwing) protection discharging AFFF at 4.1 Lpm/m^2 (0.10 gpm/ft^2) beneath the aircraft. Delivery may be through fixed or oscillating monitors. Combination ultraviolet and infrared optical detectors are required to be installed for low level detection. Supplementary low level systems are activated by the operation of a single manual release station, a single optical detector, or a single overhead rate-compensated heat detector (where pre-action AFFF sprinklers are installed). In addition, activation of any overhead sprinkler causes the low level system to operate.

A closed head sprinkler system is specified in lieu of a deluge system to overcome collateral damage from a false discharge of the overhead system. A compensating factor for the limitation of the slow activation time of the sprinklers (and possible resulting large number of sprinklers operating, as identified in the FM tests) is the requirement for optical detectors combined with low level systems. Because of the rapid response of these detectors, the primary suppression role has been shifted from the overhead system to the low level system. It should be noted that, because of reliability problems with the optical detectors, the Air Force and Army currently do not permit low level system activation using these devices.

The objective of the current research was to identify the response characteristics of overhead thermal and low level optical detection devices, identify improved optical detection devices and develop and test an improved low level AFFF suppression system. This approach extends the strategy of using the low level system as the primary fire suppression system to deliver AFFF to the hangar bay floor. In this scenario the role of the overhead system becomes secondary and no longer requires AFFF; using this strategy it was envisioned that the overhead system would be used to cool aircraft and the building structure.

5.0 ISSUES ASSOCIATED WITH CURRENT DESIGN CRITERIA

The dynamic of hangar protection has evolved in the past decade to include cost benefit considerations, risk analysis and environmental impact. These factors must be considered in relationship to evolving military needs and resources, changing aircraft designs and the

performance of hangar fire protection systems. The Navy, Air Force and Army are all pursuing alternative protection designs in response to these dynamics. Many of the issues have not been quantified; there is, however, compelling qualitative data which indicates a need for design changes. The following issues have been identified in an examination of current design criteria and systems:

1. A design objective that allows for protection of aircraft, in addition to the building structure.

2. The cost of false activation and discharges.

3. Foam and/or water entering open areas of the aircraft while it is being serviced.

4. The length of time it takes before AFFF is applied to a fire.

5. Overhead sprinkler system activation temperatures.

6. Inadequate foam floor coverage.

7. Changes to aircraft designs, particularly the hazard of jet fuel.

8. Sprinkler system design area and draft curtain criteria.

9. The effect of floor drainage systems.

10. The environmental impact of AFFF.

11. The overall reliability and maintenance of systems.

5.1 Design Objective

While the purpose of NFPA 409 is given as the protection from fire for life and property in aircraft hangars, it has been recognized that the standard provides limited protection to property within the hangar. Instead, the standard focuses on preventing the catastrophic loss of the building structure from a large fire. While the prevention of the failure of the structure is important to ensure that damage to aircraft not intimate with any fire is avoided; the Navy has come to recognize that any fire has the potential to damage multiple aircraft stored within a building. The cost of a single aircraft can approach 10 times the value of the building housing it and entire squadrons of these aircraft may be in a single hangar bay. Given these factors, protection of the contents of a hangar bay becomes much more important. Clearly the development of any new standard needs to focus on the provision of adequate fire protection measures to protect the assets and operational capabilities of the Navy.

5.2 Cost of False Activation and Discharge

Although the design of hangar fire protection systems has evolved significantly over the last decades they continue to be plagued by false activation (see Fig. 4). While many changes to design practice have already been driven by the unacceptable outcomes of a false discharge, the cost and inconvenience of these is still the single greatest motivation to improve on current design practices.

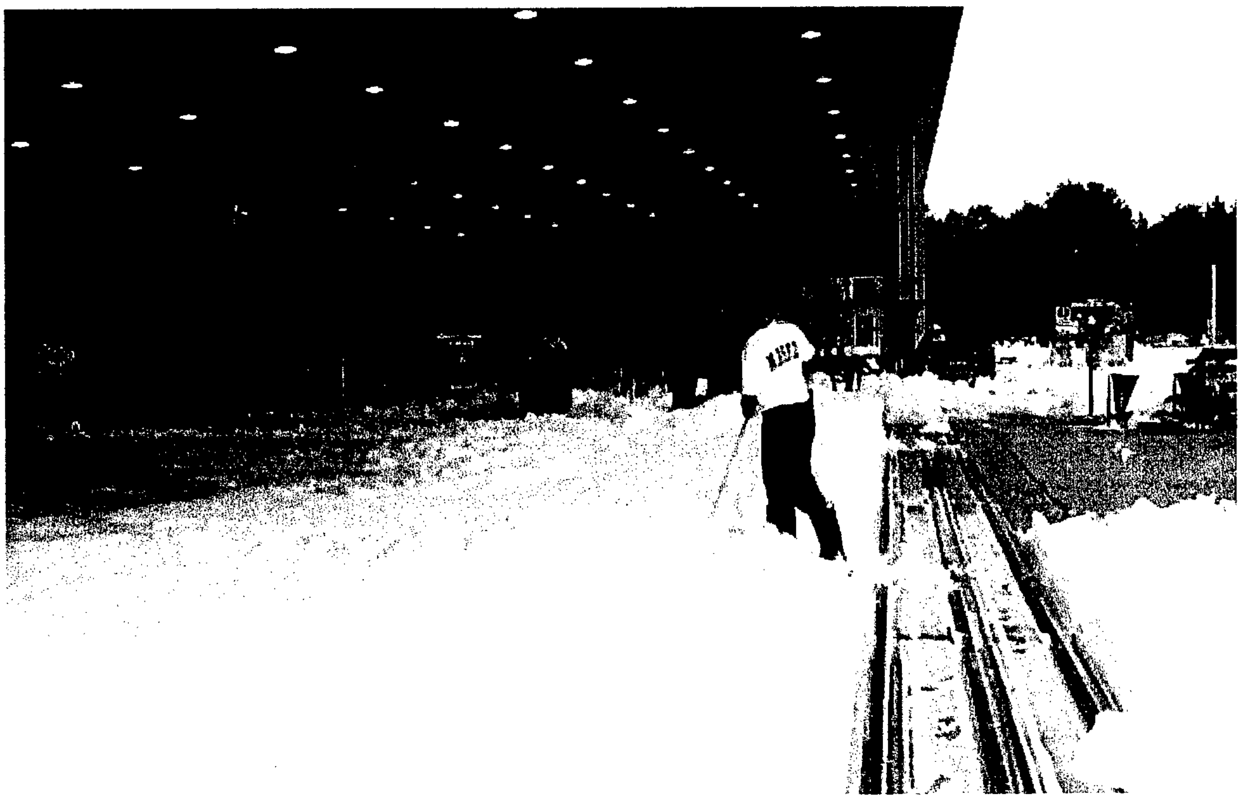

Fig. 4. Clean-up of Accidental Discharge of AFFF

There are two means to reduce the impact of false activation and discharge. First, improve the reliability of the activation of the system with the aim of eliminating false detection and activation. Second, reduce the impact of any discharge. Careful consideration of these criteria have been undertaken in the process of proposing the new design criteria described in Section 6.0 of this report.

An examination of the cost consequences of a non-fire related discharge can be summarized as:

1. Damage to aircraft,

2. Cost to recharge the AFFF system,

3. Cost of retention of AFFF runoff,

4. Cost of removal of AFFF contaminated effluent, and

5. Associated manpower costs.

The costs presented in this section are estimates based on the construction of a new, single module (high bay dimensions 30.5 by 58.5 m (100 by 192 ft)), Type I hangar as discussed in Section 2.0 Facility Description.

While damage to aircraft is often noted as the most costly result of accidental discharge it has not been possible to locate exact figures illustrating this cost. However, qualitative evidence indicates that entry of foam and/or water into the aircraft while it is open for servicing causes significant damage to the avionics. Typically this requires that every component be removed, inspected and treated for water intrusion. If a cockpit is open, the entire cockpit must be removed and all components sent to the depot for processing. While no estimates for the cost of cleaning and repairing cockpit avionics at the depot were identified, similar information for engine/nacelle fires damaged by fire fighting agent discharge is available. The Navy estimates the cost to clean and repair an engine that ingests dry chemical agent to be approximately one-half the cost of replacement [21]. It is proposed that a similar cost could be attributed to the cleaning and repair of avionics, i.e., one-half the cost of replacement.

AFFF foam concentrate meeting military specifications costs approximately \$4/L (\$15/gal). A full recharge of a system with underwing and overhead foam for a Type I hangar requires 5,900 L (1,560 gal). Consisting of approximately 3480 L (920 gal) for the overhead and 2,420 L (640 gal) for the underwing systems. The total cost of this would be \$23,600. A more likely scenario would involve a false discharge of the underwing systems only, requiring the replacement of 2,420 L (640 gal) of AFFF concentrate at a cost of \$9,600.

Containment of AFFF runoff can be extremely costly. The large flow rates of hangar fire protection systems require large retention tanks. Given that overhead systems now consist of closed head sprinklers which are very reliable (in terms of prevention of false discharge), most accidental discharges are attributable to underwing systems. Designing for full containment of a single module hangar underwing system discharge results in a containment capacity on the order of 75,000 L (20,000 gal), assuming a 10 minute discharge of AFFF solution at 4.1 Lpm/m^2 ($0.1 gpm/ft^2$). An additional allowance for clean up water retention increases this capacity to approximately 115,000 L (30,000 gal). Assuming that retention using a gravity feed system is possible (i.e., no pumping required), estimates for the cost of providing containment for the underwing discharge are between \$0.25 and 0.80/L (\$1and \$3/gal). This results in a cost of between \$30,000 and \$90,000.

Costs estimates for removing AFFF via tanker truck, to be metered to an acceptable wastewater treatment facility are approximately \$0.26/L (\$1/gal). Using the one module hangar

example, a full accidental underwing discharge of AFFF solution at 4.1 lpm/m^2 ($0.1 gpm/ft^2$) for 10 minutes is likely to cost approximately $30,000 to remove.

Manpower for clean up is likely to come from enlisted personnel working within the hangar. An estimate of the cost for this has not been assessed.

Anecdotal costs were available for the clean up of an accidental AFFF activation in an aircraft hangar at NATC Patuxent River. Initial emergency response and shut down of system was estimated to be $2,000. A fire watch was posted: the cost of this is not known. Cleanup and disposal of AFFF (contained, collected and shipped off site) was $25,000. Recharge of the AFFF system was $50,000. The total cost of activation and associated clean up was on the order of $80,000. At the time of this discharge there were no aircraft located in the hangar [22].

5.3 Agent Entering the Aircraft

In current protection designs, foam may enter the aircraft from the overhead and low level underwing systems. Steps that have been identified to reduce/eliminate this problem include:

1. Removing AFFF from the overhead system.
2. Improving the underwing foam delivery system, including limiting the height to which foam is sprayed.
3. Reducing the false activation rate.

Although there is considerable concern about AFFF entering the avionics, for land based application of AFFF the consequences may be no more serious than the application of water alone. This was a key consideration in the NAVFAC change to closed head sprinklers in the overhead system. This has greatly reduced the possible impact of the activation of the overhead systems on any aircraft in the hangar. The change means that water will not flow from all heads, as would be the case with a deluge system, on the activated overhead system.

It is desirable to eliminate the risk of foam/water entering the open cockpit or avionics panels from the underwing system (see Fig. 5). This could be achieved through a combination of more reliable detection/activation of the underwing system, and limiting the height to which foam is projected.

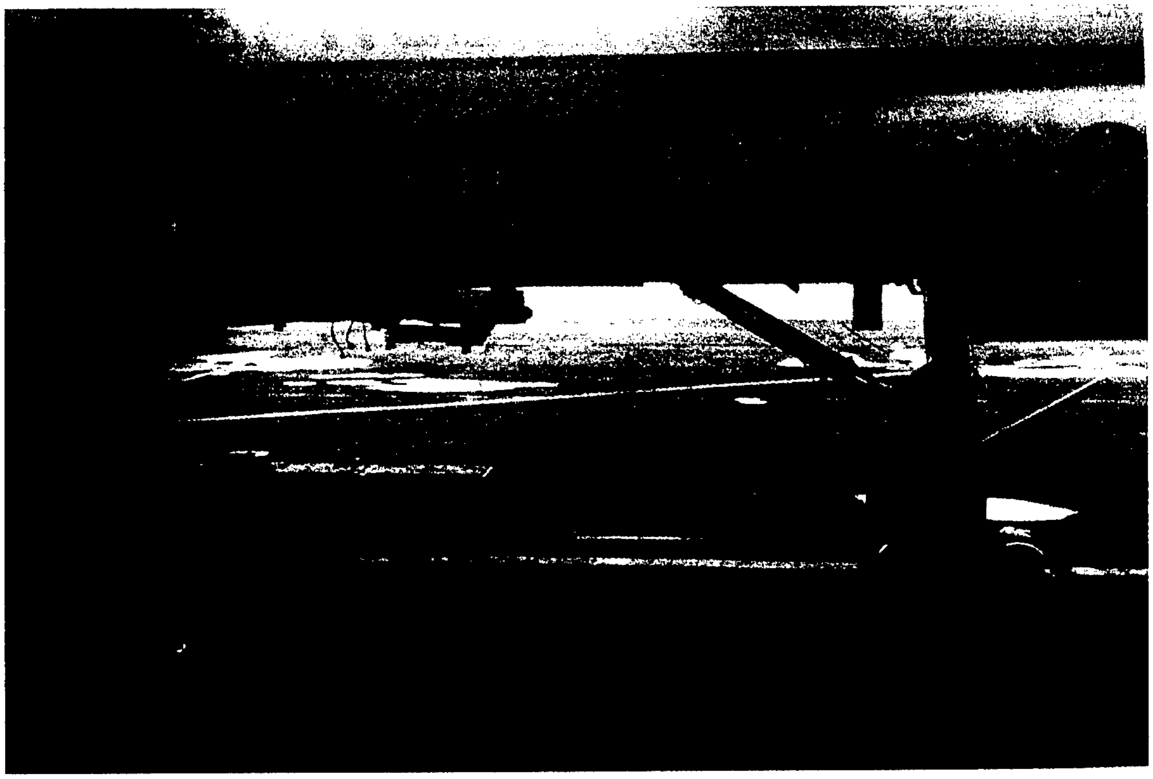

Fig. 5 . Open Aircraft Avionics/Electronics Panel

5.4 Delay in Activation for Foam Fire Protection Systems

The primary delivery system for foam is the overhead sprinkler system, which is currently required by MIL-HDBK-1008C to be a closed head sprinkler system. Foam discharge may be obstructed by aircraft wings and maintenance equipment. Foam may not be applied uniformly over the design area to the hangar floor. If there is a supplementary underwing foam delivery system activated by UV-IR detectors, it is possible that some foam is being delivered quickly, but only to the wing shadow areas. While a deluge overhead system would provide uniform delivery of AFFF, neither it, nor the closed head sprinkler system, is capable of a very rapid response. Both currently rely on thermal actuation, which may be significantly delayed in high bay hangars.

The attempts to improve the ability of high bay hangar fire protection systems to limit damage to aircraft from fires needs to ensure the application of AFFF to the entire area of any fuel spill on the hangar floor occurs in as short a time as possible.

5.5 Activation Temperature of Sprinklers

The requirements of NFPA 409 prescribe 141 °C (286 °F) standard response sprinklers. Recent research [2] demonstrated that only 79 °C (174 °F) quick response heads were effective in high bay hangars. The tests compared the activation of 79 °C and 141 °C (174 °F and 286 °F), standard and quick response sprinklers. The results indicated the superior performance of the 79 °C (174 °F) quick response sprinklers. Both activation times and the radius of thermal activation from the center of the fire were significantly better for the lower temperature quick response sprinkler.

5.6 Inadequate Foam Coverage and Monitor Nozzle Performance

Monitor nozzles were originally developed for use on flammable liquid tank farm fires. Their transition to use in hangars has been problematic. These problems include:

1. Blockage of nozzles by placement of equipment and airplanes.
2. Difficulty in maintaining correct angles of operation.
3. Failure of the nozzles to operate properly due to lack of maintenance.
4. Deliberate tampering with nozzles by personnel to prevent the possibility of their discharge into an aircraft.

In many cases, monitor nozzles are not in service in locations requiring AFFF protection (see Fig. 6, in which nozzles have been aimed directly at the ceiling of the hangar bay). Such is the extent of these problems that NAVFAC has moved away from installing oscillating monitor nozzles and currently encourages the use of fixed monitor nozzles. The inability of monitor nozzle systems to reliably deliver foam to the floor was the initial motivation behind attempts to develop a better low level AFFF delivery system.

5.7 Suppression System and Draft Curtain Design Criteria

Current requirements for the assessment of overhead sprinkler design areas are based on engineering judgement. As the building height increases, the sprinkler system design area also increases. The design area requirement is expressed as a "radius rule." Table 5 shows the radial distances for varying building heights. As the roof or ceiling height increases the water supply is

required to be sufficient for the operation of the largest number of operated systems. It is assumed that a fire at any point will operate all systems in every draft-curtained area that is wholly or partially within the radial distance for that building height. Until recently, no large scale fire testing had been undertaken in high bay spaces to challenge or validate these design assumptions. Furthermore, the sprinkler design area of operation adopted by MIL-HDBK-1008C has not been modified from those presented in NFPA 409 to reflect the NAVFAC change from a deluge sprinkler to closed head sprinkler system.

Fig. 6 . Photograph of Incorrectly Positioned AFFF Monitor Nozzle

Table 5. Sprinkler System Radius Design Area Rules

Maximum Roof or Ceiling Height	Radial Distance
7.5 m (25 ft) or less	15 m (50 ft)
In excess of 7.5 m (25 ft) but not more than 22.5 m (75 ft)	22.5 m (75 ft)
In excess of 22.5 m (75 ft)	30 m (100 ft)

NFPA 409 also contains requirements for the provision of draft curtains. These are utilized to limit the design area of deluge sprinkler systems in situations when not all the deluge systems in a single hangar bay need operate simultaneously.

Research by NAVFAC on the thermal detection times of overhead systems [2] challenges the rationale of increasing the sprinkler design area of operation with an increasing hangar bay height. The data also indicates that draft curtains are beneficial, leading to reduced activation times for both thermal detectors and sprinklers. The motivation reducing the sprinkler system design area is the cost of providing supply water at the required high flow rates.

5.8 Changes in Jet Fuel Hazards

Previous aircraft hangar design criteria were based on the use of JP-4 as the predominant fuel, which is highly volatile. The most predominant fuel used by carrier based aircraft is JP-5. When stationed shoreside many aircraft use a similar fuel, JP-8. There is a DoD emphasis to standardize all aviation fuel using JP-8. JP-5 and JP-8 are less hazardous than JP-4 because they have a higher flash point and much slower flame spread rates [23]. During combat operations, or situations when JP-5 may become unavailable, aircraft may be fueled with JP-8 or even JP-4, resulting in a mixed fuel composition. It should always be kept in mind that a fuel mixture can take on the properties of the more volatile fuel, a mixture of 10% JP-4 and 90% JP-5 will look more like the JP-4 with the lower flash point [21].

Work has been performed to document the differences observed in various fuels. In recent Air Force research [24], an investigation of the fire threat associated with the use of JP-8 compared to JP-4 during normal hangar maintenance operations was undertaken. The conclusions of this study were that the threat of a JP-8 fuel spill ignition is greatly reduced when compared to the threat from JP-4 fuel. Under ambient hangar conditions, ambient JP-8 fuel produces insufficient vapors to support ignition. Should localized ignition occur, ambient JP-8 fuel can require 20-30 seconds until there is sufficient radiative feedback to the pool to initiate flame spread across the surface of the pool.

It should also be noted that although official NAVFAC criteria is for all aircraft to be de-fueled before entering a hangar, in reality this may not occur. The only time in which de-fueling is absolutely assured is when the fuel cell liner is to be removed. Hence, there is the potential for significant volumes of fuel to be within the aircraft while in a hangar.

5.9 Floor Drainage

NFPA 409 requirements for drainage are limited in scope. Drainage must be provided and should be adequate to prevent buildup of flammable liquids and water over the drain inlet when all fire protection systems are discharging. Recommendations from Factory Mutual (FM) are more explicit. Their published Loss Prevention Data for <u>Aircraft Hangars 7-93N</u> [25] states that the provision of proper drainage facilities is one of the most important facets of hangar fire protection. The recommended maximum spacing between trenches is 15 m (50 ft). Drainage at

the hangar bay doors only is not considered adequate. Further guidance for the design of drainage systems is given in the Drainage Systems for Flammable Liquids 7-83 Loss Prevention Data [26].

Many Navy aircraft hangars have, up until this time, been constructed with insufficient drainage (no drains or drains located only at the hangar doors). The recommendations from NFPA 409 and FM given above ensure the minimization of fuel spill areas and transit time for fuel to reach the drains, thereby reducing the threat from a fuel spill.

5.10 Environmental Impact of AFFF

AFFF is potentially toxic to aquatic life, may foam when present in ground water and, may upset filtration systems when introduced into water treatment facilities. Depending on applicable jurisdictional requirements, runoff from discharges in aircraft hangars may not be allowed to enter a sewer without a period of decomposition and may not be allowed to enter surface or ground waters. A review of AFFF environmental issues was performed by an NFPA Task Group [27]. In 1990 the reporting of releases of more than 1 lb of the glycol ether category of chemicals was required by the Clean Air Act Amendments. Diethylene glycol butyl ether (DGBE), a common component of AFFF, is a member of the glycol ether family and as such required reporting to the EPA. The EPA issued a final rule in 1995 on several broad categories of chemicals including glycol ethers. The EPA has assigned no reportable quantity to any of the glycol ethers at this time. Thus there is no longer a reporting requirement for the use of AFFF. In the future, however, the EPA may look at some individual chemicals within the categories to determine whether reporting should be required. The EPA states that under Comprehensive Environmental Response Compensation and Liability Act liability continues to apply to releases of all compounds in the glycol ether category, even if reporting is not required. Parties responsible for releases of glycol ethers are liable for the costs associated with cleanup and any natural resource damages resulting from the release. Although the use of AFFF for actual fire fighting purposes is not considered a spill, retention may still be required.

Current methods for AFFF disposal are retention followed by removal and disposal. Disposal may occur either on-or off-site.

5.11 Overall System Reliability and Ease of Maintenance

Many of the problems outlined in this Section related to the performance of existing aircraft hangar fire protection systems can be attributed to system reliability and lack of adequate maintenance. At all times during the development of the new approaches to fire protection detailed in the following section, the developers have been especially mindful of these issues. All alterations to the design of fire protection systems are intended to provide new systems with higher reliability that require limited maintenance to function appropriately.

6.0 PROPOSED REVISED METHODOLOGY

6.1 Objectives

The objective of the revised methodology for protecting military aircraft is to limit the damage to high value aircraft. Specifically, there should be assurance to a high degree of probability that only those aircraft intimately involved with the initial fire incident are susceptible to sustain any significant damage. Additionally, the design of a new fire protection system should:

1. Reduce the number of false activations.

2. Reduce the impact and cost of any false discharge.

3. Improve the overall reliability.

4. Reduce the maintenance and upkeep requirements.

5. If possible, reduce the capital cost.

The system proposed to meet these objectives includes:

1. A low level AFFF system with low profile nozzles designed for a high degree of reliability and low maintenance requirements. This is the only system in the hangar proposed to use AFFF. It consists of evenly distributed nozzles protecting the entire hangar bay floor. It takes the primary role for aggressive attack of flammable fuel spill fires.

2. A closed head water only overhead sprinkler system designed to protect the building structure and provide cooling to adjacent aircraft.

3. An improved optical detection system to activate the low level AFFF system. Improvements focused on limiting false discharges and reducing system activation time to limit damage to aircraft.

4. Installation of appropriate drainage systems to limit any spill pool size and contain AFFF effluent.

6.2 Suppression System Design Basis and Criteria

A review of a number of recent studies was performed to provide a technical basis for aircraft hangar fire protection systems. An important factor in the analysis is the maximum fire

size judged to be acceptable in a hangar scenario. The report, which documents the potential for improved optical detection performance [6], identified maximum fire sizes to achieve the design objective of limiting damage to adjacent aircraft. Damage criteria to adjacent aircraft was based on an 8.1 mm thick aluminum target achieving a surface temperature between 100 and 150 °C (212 and 302 °F) (i.e., critical temperature of adjacent aircraft aluminum skin). Similar criteria could be established for composite materials or adjacent bare/unprotected steel columns. Five fire scenarios were evaluated, with the time to reach damage criteria at distances of 3.0, 6.1 and 9.1 m (10, 20 and 30 ft) from the point of ignition of a fuel spill fire.

Assuming prompt times for detection (up to 60 s), system activation (20 s) and fire control (30 s), the analysis shows that collateral damage is unlikely to occur at a distance of 9.1 m (30 ft) for even large fires (i.e., a growing 10 MW fire). Similarly, targets within 6.1 m (20 ft) can be protected for smaller fires (< 6 MW). Assets within 3 m (10 ft) may or may not be damaged by relatively smaller fires (1 MW). Items within 3 m (10 ft) for fires larger than 1 MW are likely to be damaged.

It is the role of the low level AFFF and associated activation systems to meet and overcome the challenge that these fires present to adjacent aircraft. The primary role of the low level AFFF system is the control/suppression of flammable liquid pool fires. In this case rapid detection, e.g., with optical detectors, is required to attack the fire as soon as possible, thereby limiting its size and preventing collateral damage.

Separate studies were initated to develop new low level AFFF delivery technologies and to identify appropriate optical detector technology. The report detailing The Development of a Prototype Low Level AFFF Nozzle System for U.S. Navy Aircraft Hangars [7] gives detailed design objectives and performance characteristics of a new low level AFFF delivery nozzle. Further development has led to the commercial production of an appropriate nozzle. The optical detectors testing report [6] was an intensive investigation of commercially available optical detectors, which focused on their speed of detection and ability to reject false fire signatures. The application of these studies to the design criteria for military aircraft hangars is discussed in the following sections.

Further consideration should be given to the role of the overhead sprinkler system. The stated objective is to protect the structure and provide some cooling to adjacent aircraft. However, it should be recognized that aircraft and equipment in this scenario could be severely damaged or destroyed. The pursuit of this objective inherently assumes some failure of the low level system to control/suppress the fire in its incipient stages. One could adopt the 10 MW fire size previously described as the design fire for the overhead system. However, this size seems unrealistically small, as the uncontrolled fire will continue to grow until sprinkler activation occurs. Hence the selection of a 30 MW fire appears to be more appropriate. Obviously damage to aircraft would spread beyond the 9.1 m (30 ft) limiting distance discussed above. In this scenario, however, the larger fire can be withstood for some time period before any critical structural damage to the building would occur. A key factor is the ceiling height of the hangar. Fire tests, with detailed temperature and sprinkler activation data, for this size of fire, located in high bay spaces, are limited. The only such data available is in the Analysis of High Bay Hangar

Facilities, which details tests of fires up to 33 MW in spaces with heights of 15 and 22 m [2]. A review of the NIST/Navy data focused on the size of fire and thermal characteristics at the ceiling as a function of hangar height, detection element rating and use of draft curtains. This review was intended to provide design criteria for the overhead sprinkler system design area, whether draft curtains should be provided and if so what area they should cover and to investigate the appropriateness of current specifications of a sprinkler to be used the closed head system.

6.2.1 Low Level AFFF System

Considerable potential damage to aircraft avionics has been noted from the application of foam and/or water to open areas of the aircraft during maintenance operations. Two changes to criteria are proposed that will reduce the likelihood of this occurring. First, a new underwing foam delivery system has been proposed [7]. The new design should reduce overspray of AFFF (see Section 6.2.1.1). Second, the application of foam from the overhead sprinkler system will be deleted. This reflects the shift of the primary fire suppression role for flammable liquid fires to the underwing system. Ceiling sprinklers will apply water only and their role for a flammable liquid spill fire scenario will be the cooling of adjacent aircraft and protection of the structural integrity of the hangar.

There were a number of concerns associated with the removal of AFFF from the overhead delivery system, specifically the effect water from the overhead system on the integrity of the floor level foam blanket. A separate study [5] has demonstrated that discharge of water from overhead onto the floor level foam, at rates significantly greater than the proposed water application rate, does not disturb the foam blanket while AFFF is being discharged. This was also observed in the FM turret tests [13]. Removal of the overhead foam means that the reliable performance of the underwing system becomes vital. The goals for the new underwing delivery system were to: adequately prevent burn back; prevent spreading of any pool fire; distribute agent to all floor areas susceptible to pooling fuel; reduce the time taken to apply foam to the hangar bay floor; and, significantly reduce or eliminate the possibility of foam entering any open areas of the aircraft.

It should be noted that although there are numerous anecdotal reports that AFFF is more damaging to aircraft avionics than water alone, no written evaluation of its effects were identified to substantiate this claim. It appears that the distinction between the corrosive nature of AFFF made from sea water and that made from fresh water may have been lost. The risk associated with AFFF should be correlated with the risk associated with just water entering the open avionics of an aircraft. The methods of repair of AFFF affected aircraft are detailed in various manuals. The Aircraft Weapon System Cleaning and Corrosion Control Manual (NAVAIR 01-1A-509) [28] presents different cleaning requirements for AFFF affected parts based on whether the AFFF is produced from fresh or salt water. For exposure to AFFF from fresh water, parts should be cleaned with aircraft cleaning solution, scrubbed, rinsed, dried and covered with water displacing corrosion preventative compound. A note is also provided indicating that fresh water AFFF is not expected to be corrosive. A slightly different position is taken in the NAVAIR Avionic Cleaning and Corrosion Prevention/Control Manual (NAVAIR 16-1-540) [29]. Here, the cleaning of all electronics, avionics and wiring exposed to any fire fighting agent is the same as for exposure to saltwater. The implication from this manual is that the potential for corrosion from fire fighting agents is the same as saltwater.

The surfactant in AFFF will tend to make solution penetrate more deeply into parts/equipment, which may make clean up more difficult. The fact remains that regardless of the corrosivity of AFFF, the motivation for its prevention from entering the aircraft still exists. Any steps that can be taken to prevent this occurring while the aircraft is within a hangar will prevent the need for costly rebuilding.

6.2.1.1 Low Level Design Criteria

The new low level fire extinguishing system was required to have fire fighting capabilities equivalent to the existing foam systems, be less likely to be effected by obstructions and reduce the likelihood of damage to exposed aircraft electronic equipment. In order to achieve these objectives, the following set of design parameters were developed [7]:

1. The low level system should be designed to deliver 4.1 Lpm/m^2 (0.1 gpm/ft^2) of AFFF, evenly distributed over the entire hangar bay floor for a period of not less than 10 minutes;

2. The system should operate at a pressure of 2.8 bar (40 psi);

3. The nozzles should provide coverage to a distance of 6.1-6.7 m (20-22 ft) from the drainage trenches in which they are located (centerline of two parallel trenches spaced 15 m (50 ft) apart) and

4. The spray pattern height of the nozzle should not exceed 0.3 m (1 ft) above the deck.

The nominal AFFF application rate of 4.1 Lpm/m^2 (0.1 gpm/ft^2) was selected based on current design practices [1]. The capabilities of a low level AFFF system, including deck-mounted nozzles, to effectively control and extinguish aviation pool fires at 4.1 Lpm/m^2 (0.1 gpm/ft^2) is well documented as described in Section 3.3. The proposed design rate is greater than design rates, which have been demonstrated to be adequate for a similar application where deck-mounted AFFF nozzles protected aircraft carrier flight decks. The 10-minute foam discharge requirement has historically been incorporated in foam design standards (e.g., NFPA 16 [30]) as a reasonable time for control and extinguishment while the fire department is notified and arrives on the scene. The Navy also uses these criteria as a reasonable time for fire department notification and arrival. At most Navy facilities with aircraft hangars, crash rescue vehicles with AFFF turrets/handlines respond to the incident in addition to structural fire fighting vehicles.

The nozzle operating pressure was selected based on standard commercially available pump performance characteristics and preliminary estimates of friction loss for the systems and the minimum anticipated supply pressure.

The spray pattern radius requirement of the nozzle is 6.1-6.7 m (20 to 22 ft). This is slightly less than the full coverage area of 7.5 m (25 ft) between trenches. This is considered

acceptable because the AFFF/water solution has sufficient flow velocity upon impact with the deck to flow over the remaining 0.9 to 1.5 m (3 to 5 ft) in a reasonable amount of time, e.g., 30 seconds.

The spray height requirement was selected to prevent AFFF from being discharged into open electronics compartments and causing collateral damage. Additionally, NAVFAC personnel have indicated that tool carts, which are the most common obstruction found in the hangar, could be raised to allow the AFFF/water solution to flow under the cart.

In order to achieve relatively uniform discharge patterns from each nozzle, the pressure and flow rate of AFFF solution to each nozzle must be as close to the design flow and pressure criteria as possible. This can be achieved using a combination of oversized piping between nozzles to keep friction losses to a minimum, flow regulating valves (operated by setting the downstream pressure) and symmetrical system design where possible to keep maintain equal flow/pressure distribution.

6.2.1.2 Nozzle

From the nozzle performance criteria in Section 6.2.1.1 and the prototype nozzle development [7], a commercial sprinkler manufacturing company (The Viking Corporation) undertook the further development and manufacture of a low level nozzle. The nozzle produced for commercial sale (named "Grate Nozzle") has the following performance:

1. A nozzle operating pressure of 2.8 bar (40 psi);

2. An average flow rate from each nozzle of 579 Lpm (153 gpm);

3. An average K for the nozzle of 23.6; and

4. A maximum spacing criteria for the nozzle of 7.5 by 15 m (25 by 50 ft).

The performance characteristics of the commercial nozzle have been demonstrated in an evaluation at Underwriters Laboratories, Inc. [31]

Initial low level systems designs incorporated the use of a 180° spray pattern nozzle to be installed in trenches located along hangar walls. As the design study progressed it became apparent that such locations for drainage trenches were impractical. Field observations indicated that typically the side walls of the hangars were used to store equipment, and in many situations semi-permanent rack storage was erected in this locations. Recent designs for new hangars have drainage trenches set a minimum of 3 m (10 ft) from side walls.

6.2.1.3 Zoning

It is intended that the low level system will cover the entire hangar bay floor with AFFF. However it is also recognized that in some circumstances this may not be feasible or there maybe the possibility of using zoning to reduce capital installation costs with insignificant reduction to

overall system reliability. For example, significant costs could be incurred where the design would require the installation of new large water supplies. In these situations, relief from the requirement for agent discharge over the entire hangar floor is considered acceptable. This should be evaluated on a case by case basis. In those situations, fire detection zoning may be utilized to achieve the desired floor zoning, without compromising overall system reliability.

6.2.1.4 Deadman Switch

A deadman activation station will be provided in the hangar bay to stop the flow of AFFF solution in the event of an accidental discharge of the low level system. This should be achieved by interrupting the flow of both water and foam concentrate using a "deadman" type switch. Continued manual activation of the station will be required to maintain system shutdown.

6.2.1.5 Testing

A test header is to be provided so that full flow acceptance tests may be conducted, at appropriate operating flows and the AFFF solution from these tests retained. In addition solution is sampled during these tests to ensure proportioning at the appropriate ratio. As the system pressure is controlled and the nozzle system is a deluge system, each low level system has a single operational flow rate. Each system test header should be designed to give a flow representative of the system flow.

6.2.1.6 Water Only Flow

For flushing purposes and possible cleaning of the hangar floor, it is necessary to be able to flow water only from the low level system. This operation is available to qualified maintenance personnel who will need to close the foam concentrate control valve and manually activate the low level deluge valve. Water flow from the nozzles will occur without initiating the flow of foam concentrate and without causing the foam concentrate pumps to activate.

6.2.2 Overhead Sprinkler System

One of the thrusts to reduce the impact of foam systems on aircraft was the removal of foam from the overhead system. Prior to this occurring, motivation for the change of the overhead system from a deluge sprinkler system to a closed head sprinkler system was driven by the same goal. Combination of these two changes led to the new design criteria for a closed head water only overhead sprinkler system. A number of other changes are proposed. These can be summarized as follows:

1. The minimum application rate of the sprinklers should be increased from 6.6 Lpm/m^2 (0.16 gpm/ft^2) to 6.9 Lpm/m^2 (0.17 gpm/ft^2).

2. New criteria for the sprinkler system design area and draft curtain locations should be established.

3. The sprinklers should be 79 °C (174 °F) quick response (QR) type.

6.2.2.1 Application Rate

The removal of foam from the overhead sprinkler system means that the minimum required application rate of 6.6 Lpm/m^2 (0.16 gpm/ft^2) for AFFF from NFPA 16 and NFPA 409 are no longer applicable. The application rate criteria for the water only overhead system will revert to what is currently prescribed for water only systems in NFPA 409, 6.9 Lpm/m^2 (0.17 gpm/ft^2).

6.2.2.2 Sprinkler System Design Area and Draft Curtain Criteria

Current requirements for the assessment of draft curtain spacing and overhead sprinkler design areas are based largely on engineering judgement. Draft curtain spacing was originally developed for thermal detector actuation of deluge systems, with spacing based on the size (area) limitations of deluge suppression systems in NFPA 13 (which limits the area of any deluge system to 1,394 m^2 (15,000 ft^2)). No specific consideration has been given to draft curtain requirements for closed head sprinkler systems in hangars. Recent NIST/NAVFAC research [2] indicates that the provision of draft curtains is beneficial to the activation of both heat activated detectors and closed head thermally actuated sprinklers. However, NFPA 409 currently only requires draft curtains between deluge sprinkler systems when not all deluge systems in the hangar will operate simultaneously. The overhead sprinkler system design area is currently calculated using an incremental radius rule related to the height of the hangar bay. As the ceiling/roof height of a hangar increases the design area, measured radially from any point within the hangar, also increases. Results from the NIST/NAVFAC high bay hangar fire tests indicate that, for closed head sprinklers, this requirement may not reflect the actual number of sprinklers that would be operated. Results show that as the hangar bay height increases, the likely number of heads operated decreases.

In an attempt to quantify appropriate design area/draft curtain guidelines, a review of the NIST/NAVFAC data was performed. The fire size and temperature profiles at the ceiling were analyzed as a function of the hangar height, draft curtain location and sprinkler thermal element rating. The focus of this analysis was on a 33 MW design fire, since this will result in the quickest activation time (i.e., best shows the effects of height and temperature effects).

A summary of these tests is presented in Table 6. Typically, the inclusion of draft curtains confined the hot gas layer to a smaller area, resulting in faster and greater localized temperature rises. More closed head sprinklers were activated in shorter times (or shorter activation times for thermal detectors). This effect is clearly illustrated by Tests 6b and 8, where the smaller fire size with the draft curtains gave a greater radius of sprinkler activation. This demonstrated and confirmed the benefit of draft curtains in the design of hangar actuation systems.

To further assess the effect of draft curtains in the 22 m tests, the maximum temperatures of thermocouples located immediately inside and outside the draft curtains was reviewed. Table 7 compares the maximum thermocouple temperatures, the time at which they occurred and the steady state size of the test fire. The thermocouples were located on either side of the draft curtain at the southern end of the test bay, approximately 0.3 m from the ceiling. The fire was located at the center of the 14.4 m by 45.8 m (678 m^2) draft curtained area.

Data for the 33 MW test fire indicates a difference in temperature across the draft curtain of 70 °C (158 °F). Peak temperatures were 212 °C (414 °F) and 142 °C (288 °F) respectively. It can be concluded that, for this size of fire, it is possible for a small number of closed sprinkler heads in an adjacent bay to activate. Unfortunately, temperature alone cannot be interpreted to indicate sprinkler activation. Two factors indicating that the number of heads activated in adjacent bays would be small are: (1) in the bay immediately over the fire, thermocouple readings of approximately 140 °C (284 °F) were recorded at the time that 79 °C (174 °F) sprinklers activated; and (2) the cooling of the hot layer by activating sprinklers is not accounted for in these tests.

Table 6. Sprinkler Response in 15 and 22m High Hangar Facilities [2]

15 m Facility						
Test	Max. Fire Size (MW)	Draft Curtains[1]	Number of Sprinklers Activated		79 °C Max Radial Response (m)	141 °C Max Radial Response (m)
			79 °C QR	141 °C QR		
Test 7	5.6	N	3	0	3.1 (none @ 6.1)	None
Test 5	6.8	Y	4	0	6.1 (none @ 9.1)	None
Test 6b	7.7	Y	11	0	9.1 (none @ 11.6)	Some areas > 141 °C
Test 8	12.6 (Est.)	N	6	0	6.1 (none @ 9.1)	Some areas > 141 °C

22 m Facility						
Test Name	Max. Fire Size (MW)	Draft Curtains[2]	Number of Sprinklers Activated		79 °C Max Radial Response (m)	141 °C Max Radial Response (m)
			79 °C QR	141 °C QR		
Test 14	7.9	Y	6	1	3.1 (none @ 6.1, one at 9.1)	3.0 (none @ 6.1)
Test 17	14.3	Y	12	4	15.2	3.0 (none @ 6.1)
Test 20	14.6	Y	9	5	12.2 (none @ 15.2)	3.0 (none @ 6.1)
Test 15	15.7	Y	14	5	15.2	6.1 (none @ 9.1)
Test 21	33	Y	14	11	15.2	15.2[3]

Abbreviations: N/S – North/South; E/W – East/West; QR – Quick Response.

1 Located 9.15 m N/S and 12.2 m E/W from the center of the fire.

2 Located 7.4 m N/S from the center of the fire, building walls 22.9 m E/W from the center of fire.

3 Activated at 6.1 m in all directions. Activated at 9.1, 12.2 and 15.2 m in the west but not east direction.

NFPA 409 currently requires a larger sprinkler design area for a greater roof height. Comparing Test 6b to Test 14 from Table 6 indicates that, for the same fire size, six 79 °C (174 °F) quick response (QR) sprinklers were activated at the higher height while in the lower height hangar this number increased to eleven. Apparently, the plume entrained cool air, significantly reducing the likelihood of sprinkler activation at the higher ceiling height.

Table 7. 22 m High Facility Thermocouple Temperatures on Either Side of Draft Curtain [2]

Steady State Heat Release Rate (MW)	Inside Draft Curtain		Outside Draft Curtain		Temperature Difference Across Draft Curtain (°C)
	Time (s)	Maximum Temperature (°C)	Time (s)	Maximum Temperature (°C)	
7.9	1268	90	1244	65	25
15.7	853	179	853	106	73
7	667	62	677	36	26
14.3	694	168	670	105	63
4.9	770	63	780	47	16
9.1	448	95	448	46	49
14.6	1055	155	1083	106	49
33	431	212	476	142	70

The potential to reduce sprinkler design area in high ceiling height facilities can be understood when one considers that NFPA 409 requirements are intended to apply to deluge systems. In this case, the activation of a heat detector at the ceiling activates an entire deluge sprinkler system. The change to closed head systems will result in the operation of only those heads exposed to a large enough temperature increases to cause their activation.

Using a 30 MW design fire, an estimate of a reasonable sprinkler design area for a closed head system in a high bay (e.g., 22 m) facility can be made. A closed head sprinkler design area approximately equivalent to the draft curtain area provided appears to be appropriate. The size of this area in the NIST/NAVFAC tests was 678 m^2 (7,298 ft^2), with dimensions of 14.4 m (47.2 ft) by 45.8 m (150.3 ft). If a factor of safety of 2 was applied, the resulting design area would be approximately 1,400 m^2 (15,000 ft^2).

Recognizing the benefit of draft curtains, the presented test data and the recommended sprinkler design area of 1,400 m^2 (15,000 ft^2) into consideration, draft curtains should be installed to create a maximum coverage area of 700 m^2 (7,500 ft^2). This gives at least two draft curtain areas for each sprinkler design area for closed head systems. The recommended design area applies specifically to a hangar height of 22 m or greater. It also may be reasonable to extend this to lower height hangars, as there will be some benefit in the speed of sprinkler activation for these situations.

Further investigation to verify this concept could be performed by applying field models. It would be possible to assess the impact of various fire sizes on lower hangar heights using such a model. The change of temperature over the roof area could be investigated given various draft

curtain locations. From this, the appropriate design areas for lower hangars could be identified. A similar approach could also be utilized if the effect of a design fire greater than 30 MW fire was deemed necessary.

Summarizing, the following design criteria have been proposed:

1. The design area for overhead water only sprinkler systems in Type I military aircraft hangars should be 1,400 m^2 (15,000ft^2).

2. Draft curtains should be installed. The maximum roof area of any draft curtain section should be 700 m^2 (7,500ft^2).

Specific designs may require interpretation and flexibility in applying these guidelines.

6.2.2.3 Sprinkler Temperature Rating

The NIST/NAVFAC high bay study also recommended changing the thermal element of the closed head sprinkler previously specified. NFPA 409 currently specifies standard 141 °C sprinklers. The results of the high bay tests presented in Table 8 indicate significantly faster activation times and a greater radius of sprinkler activation for 79 °C (174 °F) quick response sprinklers. Based on these test results the faster response, lower operating temperature sprinklers have been adopted as design criteria.

Table 8. Sprinkler Activation Times in 15 and 22 m High Hangar Facilities [2].
(time in seconds)

15 m Hangar						
Test #, Fire Size & HRR	Distance of Sprinkler from Center of Fire		79 °C QR	141 °C QR	141 °C Std	141 °C Std
#5 2m Dia 6.7 MW	3.1 m Radius	N, S, E, W	192, 196, n, n	n, n, n, n	n, n, n, n	n, n, n, n
	6.1 m Radius	N, S, E, W	395, n, 199, n	n, n, n, n	n, n, n, n	n, n, n, n
#6b 2.5m Dia 7.7 MW	3.1 m Radius	N, S, E, W	n, 88, 147, 104	n, n, n, n	n, n, n, n	n, n, n, n
	6.1 m Radius	N, S, E, W	144, 140, 251, 207	n, n, n, n	n, n, n, n	n, n, n, n
#7 2m Dia 5.6 MW	3.1 m Radius	N, S, E, W	585, n, n, 403	n, n, n, n	n, n, n, n	n, n, n, n
	6.1 m Radius	N, S, E, W	n, n, n, n	n, n, n, n	n, n, n, n	n, n, n, n
#8 2.5 m Dia 12.6 MW (est.)	3.1 m Radius	N, S, E, W	366, 366, 359, 403	n, n, n, n	n, n, n, n	n, n, n, n
	6.1 m Radius	N, S, E, W	467, n, n, n	n, n, n, n	n, n, n, n	n, n, n, n

Table 8. continued.

22 m Hangar						
Test #, Fire Size & HRR	Distance of Sprinkler from Center of Fire		79 °C QR	141 °C QR	141 °C Std	141 °C Std
#14 2.5m Dia 7.9 MW	3.1 m Radius	N, S, E, W	a, 361, 546, 499	n, n, n, a	n, n, n, a	n, n, n, n
	6.1 m Radius	N, S, E, W	n, n, n, n	n, n, n, n	n, n, n, n	n, n, n, n
#15 3x3 m 15.7 MW	3.1 m Radius	N, S, E, W	119, 119, 132, 142	384, 324, 444, n	501, 473, 640, n	440, 417, 501, 529
	6.1 m Radius	N, S, E, W	169, 151, 281, 174	a, n, a, n	n, n, n, n	n, n, a, n
#17 3x3 m 14.3 MW	3.1 m Radius	N, S, E, W	100, n, 121, 121	388, 378, n, 402	A, 495, 584, 575	425, 406, n, 519
	6.1 m Radius	N, S, E, W	a, 137, n, a	n, n, n, n	n, n, n, n	n, n, n, n
#20 3x3 m 14.6 MW	3.1 m Radius	N, S, E, W	115, 101, 124, 115	447, 382, 493, 503	n, n, n, n	484, n, 531, 521
	6.1 m Radius	N, S, E, W	n, 147, 165, n	n, n, n, n	n, n, n, n	n, n, n, n
#21 4.6 m Dia 33 MW	3.1 m Radius	N, S, E, W	87, 87, 91, 91	114, a, 118, 118	127, a, a, 154	127, a, 132, 132
	6.1 m Radius	N, S, E, W	a, 91, 95, 100	a, a, 136, 140	a, n, n, n	a, n, 168, n

Abbreviations: n – No activation; a – Activation, time unknown; N/S – North/South; E/W – East/West; QR – Quick Response; Std – Standard Response.

6.3 Improved Detection Design and Reliability

The successful performance of the detection system for the low level AFFF foam system is necessary for achievement of the system objectives. It has been established that collateral damage to aircraft can be prevented at a distance of 9.1 m (30 ft) for a growing 10 MW fire with prompt detection, system activation and fire control. Improved detection systems should rapidly detect an actual fire incident, while screening out false/nuisance alarm sources. A time limit of 60 seconds for detection of a plausible ignition scenario was selected as the design objective for the optical detection systems. In addition, existing optical detection systems have previously been the cause of many false activations of AFFF systems. Improvement of false alarm immunity is vital to reduce the occurrence of these incidents.

The NAVFAC/NRL/NRC optical detector (OFD) study [6] demonstrated that the lack of a performance based standard for optical detectors in hangars has been potentially limiting the use of better detection technologies. Current MIL-HDBK-1008C requirements specify the use of UV-IR optical detectors to activate supplementary underwing foam systems. However, since the origination of this requirement, optical detection technology has changed significantly and new optical detectors using triple infrared sensors (IR^3) have become commercially available. The Navy's experience in hangars and the testing results, indicate that there is great variation in the

performance of UV-IR optical detectors on the market. Some detectors appear to be more prone to false alarm yet less in detecting an actual fire. Some UV-IR detectors can perform similarly to available IR^3 detectors, however some perform significantly worse. The poor performance of some detectors in rejecting false alarms is a reflection of the lack of performance criteria requiring testing to ensure false alarm immunity.

Results from the study showed that the specification of only UV-IR optical detectors is not warranted as generally IR^3 detectors provide improved speed of detection and greater false alarm resistance. A draft performance specification for optical fire detectors for use in military aircraft hangars was produced and recommended for adoption. This specification would permit any optical detector technology to satisfy the detection and false detection resistance criteria. Until the performance specification is officially adopted and implemented, it is recommended that only IR^3 detectors be installed.

A statistical analysis was performed to identify effects of individual hangar AFFF system components on overall system reliability. A new approach for determining the reliability of fire protection systems was developed. This methodology, presented in Appendix A, utilizes fuzzy sets. Fuzzy failure probabilities, determined from standard failure rate data, were propagated through fault trees to determine probabilities of both failed-safe and failed-dangerous scenarios. A system is failed-safe if it activates in the absence of the initiating conditions (i.e., when there is no fire). A system is failed-dangerous if it fails to activate in the presence of the initiating stimuli, a fire.

The method was used for determining the reliability of a hangar AFFF system using an optical detector actuated pre-action delivery system with low level monitors. Component failure rate data from the U.S. Nuclear Regulatory Commission and Department of Energy, along with industry data, were used for valves, pumps and detectors. Specifically, electronic component failure rate data from the processing industry was applied to the optical detectors.

The example in Appendix A showed the high probability of optical detectors failing-safe as the primary source of low failed-safe reliability of the AFFF system. The high probability of no fire makes the system very sensitive to component failed-safe probabilities. For fire pumps, the high failure probability is countered by the current criteria to place two pumps in parallel. Similarly, adding optical detectors in series (i.e., two units required to alarm before system activation) could increase the system reliability at a low cost when compared to the expected loss of a failed discharge of the system.

The statistical analysis verified the need to improve optical detector performance. The effects of the new optical detector requirements on system reliability remains to be seen. The analysis in Appendix A relied heavily on electronic component failure data applied to optical detectors, rather than on spurious alarms well known, but poorly documented in the military community. A conservative approach would be to assume that the cost benefit ratio is still in favor of using multiple detection signals before system discharge. This would require adding optical detectors for redundant coverage.

6.4 Drainage

The adoption of adequate drainage for flammable liquid spills in aircraft hangars is proposed in the new low level AFFF delivery system design. By utilizing drainage trenches located 15 m (50 ft) on center to deliver the foam solution, the drainage spacing criteria identified previously from commercial requirements is adopted by default.

Currently, there is no specific Navy guidance on the containment of AFFF from a system discharge. The proposed new design would reduce AFFF discharge in the event of a non-catastrophic (i.e., non-fire) system activation. However, there is confusion on the appropriate measures to implement to reduce the environmental impact of AFFF should it be discharged. There is no coherent, scientifically based policy and strategy for designers/facility managers to guide decisions on containment of AFFF discharge. MIL-HDBK-1008C and NFPA Codes and Standards are essentially silent on the issue. The U.S. Army has published guidance [32]. For open head AFFF systems, containment to hold the full system flow for ten minutes is recommended (a greater time is recommended if the fire department cannot respond to isolate valves in this time period). For closed head systems, a containment system with a capacity for a three-minute system test flow is recommended. Local requirements and restrictions may dictate the containment design. Historically, these have ranged from no restrictions to very severe containment requirements. In one situation, the total fire protection design discharge for one-hour duration was required to be retained, in addition to the worst case storm water runoff.

There is a need to develop a rationale policy and criteria addressing AFFF discharge for hangars. This should include a review of applicable standards, an assessment of the environmental impact of AFFF, a review of local and national environmental regulations/trends and an analysis of containment options. Ideally, this analysis would involve input from all branches of the military so that there is a cohesive DoD policy.

6.5 Maintenance

The Air Force has developed an inspection, test and maintenance (ITM) guide for fire protection systems [33]. This manual describes a reliability-centered maintenance approach that details inspection, test and maintenance requirements based on the failure rates of components of fire protection systems and the effect of these failures on the successful operation of the system. Table 9 contains a breakdown of various ITM procedures for low expansion foam systems and the recommended frequency with which they should be performed. For comparison purposes, the ITM frequencies are contrasted with those recommended in NFPA 11.

Inspection, testing, and maintenance should be performed as a minimum to the level specified by the ITM Guide. Alternatively, a separate maintenance frequency schedule should be adopted by the Navy. This should be based on the approach used by the Air Force, using additional/new/updated data from Navy-specific situation and/or other military and industrial sources.

Table 9. Inspection, Test and Maintenance (ITM) Guide for Fire Protection Systems

Inspection, Test and Maintenance Task		ITM Guide Frequency	NFPA Frequency
NFPA 11 – Standard for Low Expansion Foam	Thorough inspection and operational check to ensure: • Proper foam concentration; • Foam concentrate pump is flushed; • All equipment (proportioning and discharge is free of physical damage and leakage; • All actuators, manual and automatic, function; • Strainers are clean; and • Proper drainage pitch is maintained.	1 to 2 years	At least Annually
	Spot-check inspection of underground piping for: • Deterioration.	5 years	5 years
	Foam concentrate inspection for: • Evidence of sludging, deterioration; and • Quantity.	Annually	At least Annually

Maintenance and inspection procedures for the new low level nozzles should be developed. This includes flow of agent through the nozzles and clean out of any clogged nozzles. A clean out feature has been incorporated in the proposed design of the low level system.

6.6 Capital Cost Evaluation

For the purposes of comparing the capital cost of existing systems compared to the proposed design, an estimate of the cost of installing each system was performed. The analysis included:

1. A monitor nozzle AFFF underwing delivery system with foam/water overhead (referred to as an old system), and

2. A low level trench nozzle AFFF underwing delivery system with water only overhead (referred to as a new system).

The estimate was prepared based on a hangar of a single Type I module size (30 by 60 m (100 by 200 ft)). The installation of each system has been considered in both a new and existing hangar. Adequate water supply from a nearby grid has been assumed. Costs for AFFF effluent containment were not included. It is believed that the estimate provided is within 10% of a sub-contractors bid price to install such a system, however prices from contractors have not been

specifically obtained in preparing this data. Detailed analysis of the cost can be found in Appendix B. As always, local/regional wage and material availability variables and economic conditions will effect the costs. The objective here is to provide a comparison of cost for both and new construction and existing hangar retrofit.

The capital costs of the new system are estimated to be slightly less (~ 3% less) than those of the old system for new construction. Total cost estimates are $467,000 for the new system and $482,000 for the old system. There are two areas in which significant differences in price can be observed. The first area is in the foam storage and delivery system. The elimination of foam in the overhead system reduces the amount of foam required by more than 50% for the new system. This leads to a decrease in tank storage and concentrate pumping requirements, as well as a reduction in the equipment needs to supply and proportion the foam into an overhead system. The reduction in space required for storage of foam has not been factored into the cost savings. Overall the foam related equipment cost for the new system is approximately two thirds of the cost of the old system ($110,000 versus $160,000).

The second factor is the extent of drainage trenching required. The new delivery system requires trenches on 15 m (50 ft) centers within the hangar. In the old system, trench drains were typically spaced at 30 m (100 ft) centers. A single module hangar is likely to have 120 m (400 ft) of trenches for the old system and 180 m (600 ft) for the new system. With an estimate of $600/m ($185/ft) for the trenching, the cost comparison is $75,000 versus $112,000.

The breakdown of the estimate for an existing hangar retrofit indicates that the capital costs of the new system are greater (~ 6% more) than those of the old system. Total cost estimates are $636,000 for the new system and $600,000 for the old system. The installation of trenches is the area in which significant differences in price are observed.

For installation in an existing hangar, the overall equipment costs will remain unchanged. A qualitative assessment of the increase in equipment installation costs indicates that this would likely be similar for both systems. Hence an additional cost of $10,000 was attributed to work required to install the systems in an existing building. This was added to the overall cost.

Installation of drainage trenches where previously there were none, or where existing trench spacing is inadequate, will have a significant impact on the cost of both systems. This increase will be greater on the new system where 60 m (200 ft) more trenching is required. Historical cost data for the retrofit of a trench in a BRAC hangar project at MCBH Kaneohe, Hawaii, indicated a cost of $1000/m ($305/ft) for a 250 mm deep by 300 mm wide (10 by 12 in) trench. The cost for the 600 by 600 mm (24 by 24 in) trench required here has been estimated at approximately $1,475/m ($450/ft) (for comparison the cost of installing trenches in a new hangar was estimated at $600/m ($185/ft)). The additional 60 m (200 ft) of trench required for the new system will result in an additional $90,000 over the cost of trenches for the old system.

For larger hangar bays (i.e., spaces that consist of a number of hangar modules with no permanent physical barriers in the high bay space), zoning of the underwing foam system should

be considered. While this approach will invariably lead to a decrease in system reliability, it should be balanced with the unrealistically large water discharge rates and problems with run-off retention that are generated when a total floor discharge is required. Zoning is likely to also require the implementation of two detectors reporting an alarm condition to ensure activation of the correct underwing zone.

It is anticipated that much greater overall savings will be realized in lifecycle costs of the hangar and systems. These savings should result from the reduced number of accidental discharges and reduced costs from cleanup of AFFF overspray in the event of a false activation. No attempt has been made to quantify the lifecycle cost savings for this report.

7.0 SUMMARY AND RECOMMENDATIONS

Historically, the emphasis of hangar fire suppression systems has been the protection of the hangar structure. Originally, water deluge sprinklers were combined with heat detectors located at the ceiling. Protein foam and AFFF were later incorporated into these systems. Supplementary low level AFFF monitor systems were added to provide protection to shielded areas (such as underwing areas) where AFFF suppression from sprinklers might be delayed.

The dynamics of hangar protection has evolved in the past decade to include cost benefit considerations, risk analysis and environmental impact. Hangar systems in the Navy and DoD in general have been plagued with system operational problems. In particular, false activation of the AFFF system resulted in costly cleanup and recovery after a nuisance event. Recognizing these problems, in addition to the need to protect high value military assets (in addition to the structure), the Navy proposed a new concept for protecting hangars. It is proposed that a closed head water sprinkler system be installed to provide protection of the overhead roof structure as well as provide supplemental cooling to aircraft in the event of a fire. The primary suppression role is proposed to be shifted to a low level AFFF fire suppression activated by optical detectors. The low level AFFF systems are to be designed for minimum overspray while providing sufficient capability to extinguish a jet fuel spill fire. Improved optical detector performance is required to reduce false discharges while providing rapid fire detection to limit damage to incident aircraft.

The Navy research performed to implement the proposed new design was reviewed. This includes: actuation characteristics for thermally actuated devices at the ceiling; performance of low level AFFF when exposed to water discharge; performance specifications for improving optical detector technology and the development of a new, low level AFFF nozzle to be installed in hangar floor trench drains. This research included a hazard analysis, which established an acceptable level of system performance to prevent collateral damage of aircraft exposed to fire. The low level AFFF system and associated activation system is intended to meet this performance objective. The AFFF testing demonstrated that burn back of a foam blanket will not occur when water sprinklers are operating and the AFFF system is still operating. The research results were used to develop the low level system to protect aircraft and the building structure, reduce the likelihood of false discharges, reduce foam overspray to exposed areas of aircraft and provide

sufficient coverage of the floor area. The rationale and basis for the design to address these issues are presented in the report. Based on this review and analysis, the Navy should adopt the proposed low level system design approach, which includes the following features:

1. Low level AFFF nozzles installed in trench drains in the hangar floor, designed to:

   (a) Be flush with the hangar floor,

   (b) Provide 4.1 Lpm/m^2 (0.10 gpm/ft^2), and

   (c) Limit overspray, e.g., do not spray more than 0.9 m (3 ft) above the floor;

2. Optimized optical detectors to actuate the low level system; the performance parameters identified in the optical detector study should be implemented; in the interim, triple IR detectors should be specified; and

3. Closed head QR 79 °C (174 °F) water sprinklers in the overhead designed to discharge 6.9 Lpm/m^2 (0.17 gpm/ft^2).

The actual design of the new hangar fire protection system must also address practical considerations involving sprinkler system design areas, installation of draft curtains, installation of drainage systems, environmental impact of AFFF and overall reliability and maintenance of systems. These issues were analyzed with respect to Navy R&D results, actual NAVFAC experience and industry data. Based on this analysis, the following findings and recommendations were developed:

1. Sprinkler design area and draft curtains:

   (a) A design area for overhead water only sprinkler systems in Type I hangars of 1,400 m^2 (15,000ft^2).

   (b) Draft curtains to be installed. The maximum roof area of any draft curtain to be 700 m^2 (7,500ft^2).

2. System reliability – a generalized method, using fuzzy logic, was developed for assessing fire suppression system reliability. This method can be used to assess any fire protection system. The hangar AFFF fire suppression system was analyzed. The analysis verified that the false activation of optical detectors contributes significantly to the probability of an unwanted system discharge. The probability of an unwanted system discharge could be reduced by requiring the operation of two optical detectors, before the system is tripped. The Navy should consider requiring the activation of two optical detectors before actuation of the low level AFFF system

occurs. Since the field performance of the recommended triple IR OFD (or other detector meeting the performance specifications) is unknown, the Navy should monitor new installations. This data should be used to determine the need for dual detector actuation.

3. Trench drains should be installed a maximum of 15 m (50 ft) on center, designed to accommodate the new AFFF system and effluent drainage. Drainage design should be in accordance with nationally recognized standards.

4. The U.S. Air Force has evaluated maintenance requirements for AFFF systems. These requirements should be adopted by the Navy. Alternately, these requirements should be modified based on additional/new/updated data and experience from Navy-specific situations and/or military and industrial sources.

5. Currently, there is no specific Navy guidance on the containment of AFFF from a system discharge. The proposed new design would reduce AFFF discharge in the event of a non-catastrophic (i.e., non-fire) system activation. However, there is confusion on the appropriate measures to implement to reduce the impact of AFFF should it be discharged. There is a need to develop a rationale policy and criteria addressing AFFF discharge for hangars. Ideally, it would involve input from all branches of the military.

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APPENDIX A - METHODOLOGY FOR DETERMINING RELIABILITY OF A FOAM SUPPRESSION SYSTEM USING FUZZY SET THEORY AND FAULT TREE ANALYSIS

METHODOLOGY FOR DETERMINING RELIABILITY OF A FOAM SUPPRESSION SYSTEM USING FUZZY SET THEORY AND FAULT TREE ANALYSIS

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ABSTRACT

A fuzzy set methodology for determining the performance reliability of fire protection systems is presented. The method is then used for determining the reliability of an aqueous film forming foam (AFFF) fire suppression system. Fuzzy failure probabilities, determined from standard failure rate data, were propagated through fault trees to determine probabilities of both failed-safe and failed-dangerous scenarios. Fuzzy numbers allows expert opinions, operating conditions and large data sources to be incorporated into component failure probabilities. Fuzzy sets also offer a simple method for propagating data spreads through the fault tree analysis. Therefore, the results present both a "crisp " (nonfuzzy) number characterizing system reliability and, an indication of the failure rate data error propagation. The AFFF fire suppression system sensitivity using multiple UV-IR detectors is shown to reduce fail-safe probability of failure from 0.59 for one detector to 0.23 for three detectors.

INTRODUCTION

This Appendix outlines a new approach for determining the reliability of fire protection systems. The use of fuzzy set and fuzzy arithmetic theory to characterize component reliability is used in several areas of reliability engineering [A-1]. The most noteworthy of these is in software systems [A-2]. In addition, fuzzy logic is used in many control systems. Fire protection systems

have sparse data available on their performance. This situation is an example of a system where fuzzy is more appropriate for determining performance and reliability than standard statistical methods.

Analyzing system reliability requires the use of many sources of information which depict system performance and component failure rates. An inherent flaw with many data sources is in quality and consistency of the data collected. Traditional statistical methods for determining reliability require precise probabilities and data gathering techniques. Inconsistencies in either of these elements during the development of a statistical model can lead to inaccuracy which greatly degrades the usefulness of the results.

When examining operational systems, or system designs, and attempting to characterize performance, a rigorous probabilistic approach is not always practical. Extensive testing of systems and components may be cost prohibitive, or for some other reason, impossible. Fire detection and suppression systems are a perfect example of this situation. Finding sound reliability data at either the system or component level is challenging. A significant number of systems have no records of testing and maintenance and for some suppression systems, periodic testing is not possible. For many of the components of a fire protection system, a failure may be a very rare event, on the order of a few per million hours of operation. Finding this information, predicting a reliability and determining its relevance to a particular system is often a questionable practice.

Much of the data used to characterize fire protection systems is the expert opinions of engineers and the experience of system users. Some systems used for fire protection, like sprinklers or foam suppression systems, may work to a degree but not completely. These systems may still have a positive effect on controlling a fire, while not performing at the 100 % level. All of these factors tend to degrade the results obtained from current statistical methods used to determine a fire protection system's overall reliability.

In contrast, the use of fuzzy sets to describe subsystem and component reliability has significant advantages. For example, a fuzzy set will allow input from a wide range of data sources collected under many different conditions. Additionally, the use of expert opinions and other linguistic options can be logically incorporated and used in determining reliability and performance.

As an illustration of this methodology the performance reliability is evaluated in a fault tree analysis for an AFFF fire suppression system using fuzzy numbers. This paper describes fuzzy set theory and fuzzy arithmetic to the extent needed for this study. A method for determining fuzzy reliabilities from failure rate data sets is proposed and alternatives explored. The analysis include both conditional and unconditional failed-Safe (FS) and failed-Dangerous (FD) scenarios [A-3]. The reliability results and their possibility distributions are derived for both scenarios.

FUZZY NUMBERS

In traditional set theory, a set, A, is defined as the elements of some universe X, that satisfy the membership requirements of A. Numbers are either members or nonmembers of the set. In fuzzy set theory, elements may have varying degrees of membership in A, from total membership to no membership. The membership function, $\mu_A(x)$, has values from 0, representing no membership, to 1, representing total membership [A-1]. The fuzzy number is commonly defined by the points at which the membership function is equal to zero, one and zero. Two classes of membership grades commonly used in reliability analysis, the triangular, defined by the points $[\mu_1/a1, \mu_2/a_2, \mu_3/a_3]$, and trapezoidal, defined by $[\mu_1/a_1, \mu_2/a_2, \mu_3/a_3, \mu_4/a_4]$ as shown in Figure A-1. This convention reflects the set element (μ_i)/membership function value (a_i)

Arithmetic operations can be performed on fuzzy numbers using interval arithmetic [A-1]. Fuzzy set intervals having the same membership function values are combined according to the specific operations (this is discussed in later detail in a later section). If the interval at

membership function value, μ, is $[a_1,a_2]$ for fuzzy number A, and $[b_1,b_2]$ for B, then the following equations illustrate operations used in the propagation of reliability.

$$ {}^{\mu}[a_1,a_2] \times {}^{\mu}[b_1,b_2] = {}^{\mu}[a_1b_1,a_2b_2] \tag{1} $$

$$ 1 - {}^{\mu}\left[a_1,a_2\right] = \left[(1-a_2),(1-a_1)\right] \tag{2} $$

DEVELOPING FUZZY NUMBERS FROM DATA

When data is reported on a confidence interval the mean value is said to be the most probable representation of the measured or observed event. A probability distribution function has the form:

$$ \int_{-\infty}^{\infty} f(x)dx = 1 \tag{3} $$

for all x where;

$$ f(x) \geq 0 \tag{4} $$

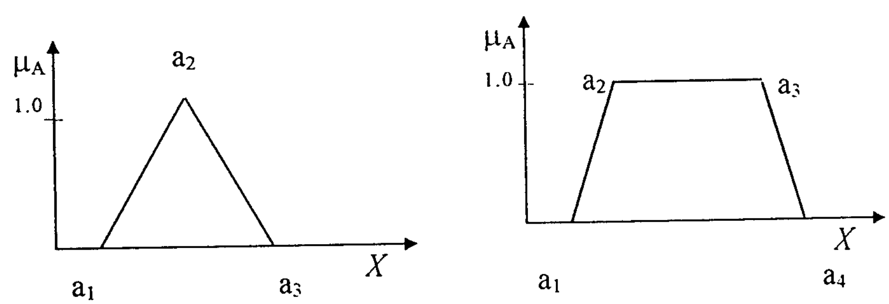


Figure A-1. TRIANGULAR AND TRAPEZOIDAL SHAPE MEMBERSHIP FUNCTIONS.

Possibility theory defines a possibility distribution function also defined on the interval from [0,1]. A possibility distribution provides a measure of uncertainty [A-1]. However, a possibility distribution function is not required to sum to 1 and thus provides a degree of flexibility in describing system reliability. A possibility distribution function can be defined to reflect improbable events that could be highly possible and the converse.

As an example of this, consider a system subject to a corrosive environment. Pipe rupture in a normal system is generally a rare event. However, in a pipe system operating under adverse conditions pipe failure rate may warrant weighting the higher side of the failure rate distribution. This allows the widely available industrial pipe rate data spread to reflect possible failure rates more accurately in an abusive environment. These decisions can be made by cognizant personnel involved in both system design and operation.

The fuzzy reliabilities developed here are based on the work of Zadeh [A-6] who defines the probability of a fuzzy set F as the expected value of the F's membership function [A-1]:

$$P(F) = \int_S \mu_F(x)dP \tag{5}$$

for a discrete sample space, $S = (x_1, x_2, \ldots, x_n)$

$$P(F) = \sum_{i=1}^{n} \mu_F(x_i)P(x_i) \tag{6}$$

If F is a fuzzy probability, P(x) describes the probability of an event occurring, and $\mu_F(x)$ is the membership function for F defined by the possibility distribution function.

The transition from probabilistic to possibilistic analysis is best accomplished by considering the reported relative frequencies of events as fuzzy numbers [A-7]. Possibility distribution functions can be determined from available data ranges. Possibility measures are

directly connected to fuzzy sets via the possibility distribution function [A-8]. The approach proposed by Singer [A-7] for determining a fuzzy number for frequency of occurrences in a hazard analysis is used here for guidance in assigning fuzzy reliabilities from crisp data [A-5]. Singer assumed that an event frequency was a fuzzy number. The representation of this number was assumed to be triangular with the reported value having a membership function value of 1 and values +/- 50% from the reported value had membership values of 0.1. With no data ranges available for guidance, this assumption provides a triangular fuzzy number representing the possibility distribution for an otherwise crisp number.

Much of the data available for the components of AFFF systems is presented in the form of failure rates per time period of operation with an expected mean value and high and low limits reported. The components failure rates from several sources reported by the United States Nuclear Regulatory Commission (USNRC) in the WASH 1400 Document [A-4] were said to be at 90% probability. These were compiled into one mean with upper and lower bounds. The mean failure rate was used to calculate a reliability using Equation 7, and this value was given a membership function value of 1. The failure rate data at the endpoints of the 90% confidence intervals were also converted to reliabilities and given membership values of 0.1.

$$R(t) = e^{-\alpha t} \qquad (7)$$

These values were then extended to yield the triangular fuzzy number representing the fuzzy reliability. This method provides a reasonable quantification of the spread of the data. The triangular fuzzy number represents the possibility distribution for the reliability of a particular component falling on the interval. The component failure data with the corresponding fuzzy numbers are presented in Table A-1.

As an example of assigning a fuzzy number for data having a mean value with a range of reported values [A-4], the fuzzy reliability R_f (and fuzzy probability of failure, $1\text{-}R_f$) of a check valve is determined:

$$\alpha = \text{mean failure rate (failure to open)} = \quad 1 * 10^{-4} \text{ /day} \qquad (8)$$

$$\text{upper and lower bounds} = \quad 3*10^{-4}, 3*10^{-5} \text{ / day} \qquad (9)$$

The reliability was determined for a one year period using Equation 7 for the three reported failure rates. This yielded an interval of [0.9,0.96, 0.99]. This interval was then used to determine the possibility distribution used as the membership function of the fuzzy reliability.

TABLE A-1

Component Data and Fuzzy Numbers

Event #	Component	Assessed Median	Lower Bound	Upper Bound	Fuzzy Failure Probability
17, 18	Pumps-Failure to Start	1×10^{-3} / day	1×10^{-4} / day	3×10^{-3} / day	(.08, .31, .70)
19	Pre-Action Valve-Failure to Open	1×10^{-3} / day	3×10^{-4} / day	3×10^{-3} / day	(.08, .31, .70)
11,15, 12,22	Check Valves-Failure to Open	1×10^{-4} / day	3×10^{-5} / day	3×10^{-4} / day	(.01, .04, .11)
21	Manual Valves-Failure to Remain Open	1×10^{-4} / day	3×10^{-5} / day	3×10^{-4} / day	(.01, .04, .11)
12	Pipe Gasket Failure	3×10^{-6} / HR	1×10^{-7} / HR	1×10^{-4} / HR	(.00, .03, .64)
	Sprinkler Head-Failure to Open on Demand	$<10^{-6}$ / demand			(.00, .00, .00)
23, 24	Heat Detector Failure to Alarm	.3 / 10^3 detector year			(.00, .01, .02)
4	Heat Detector-False Alarm	5.3 / 10^3 detector year			(.00, .01, .01)
9	UV-IR Detector-Failure to Alarm	108 / 10^3 detector year			(.00, .10, .20)
7	UV-IR Detector False Alarm	622 / 10^3 detector year			(.31, .62, .93)
8	Assumed Demand-Chance of Fire in Any Given Year	.05 / year	0 / year	.1 / year	(0, .05, .1)

$$\mu_f = (0.90/0.1, 0.96/1, 0.99/0.1) \qquad (10)$$

The original endpoints of the interval were then extended by 10% to get the endpoints of the fuzzy number yielding the triangular fuzzy reliability:

$$R_{F\text{ check valve}} = [\ 0/\ 0.89,\ 1/\ 0.96,\ 0/\ 0.99\ ] \qquad (11)$$

Several advantages to using fuzzy numbers to describe the data range for a given component are apparent here. A bias can be introduced by a system designer or engineer with regard to the type of use and component operating environment. Additionally, the data sets used to develop the range of data and the mean can be chosen based on their applicability to the system being studied. That range can then be assigned membership values to reflect its compatibility with the system. For the example presented above this has a great advantage over a limited data base in that all of the check valve failure rate data from the large data set is still represented, and the most applicable interval values carry more weight.

LINGUISTIC VARIABLES

A linguistic variable is a variable with values that are words rather than numbers. For example, the linguistic variable, "reliability", may have values of low reliability, high reliability, andvery high reliability. These variables are very useful in describing systems for which no failure data exists and expert opinions must be used. Linguistic values allow less specific characterizations than numerical values. An expert may know from experience a system is rather reliable but may not have data available to determine a specific numerical value. Therefore, a set of linguistic values describing reliability are defined, and an expert uses the words that best describe the system. Linguistic values assume a common understanding of the meaning of the words exist, but also accounts for the subjectivity in individual interpretations. For example, a highly reliable system would be considered by most to have a reliability somewhere above 0.7 but less than 1.0. This is well represented by triangular fuzzy numbers.

The fuzzy numbers are developed for the defined linguistic values by assigning degrees of membership to numerical values of reliability. The membership function should reflect actual knowledge of the system being studied. One membership function suggested by T. Onisawa in Equation 12, assigns degrees of membership in linguistic values for numerical reliabilities. This method uses an initial numerical probability of failure, *r*, associated with the linguistic value of

reliability to determine the distribution of numerical values and also accounts for the degree of fuzziness, m, in the initial estimate [A-9]. These values as suggested by T. Onisawa are shown in Tables A-2 and A-3.

$$F(x) = \frac{1}{1 + 20\left(\left|x - r\right|^{m}\right)} \qquad (12)$$

TABLE A-2

Linguistic Values and Associated Numerical Values

LINGUISTIC VALUE	Probabilities of Failure (r)
no reliability	0.9-1.0
low reliability	0.7-0.9
rather low reliability	0.55-0.7
standard reliability	0.45-0.55
rather high reliability	0.3-0.45
High reliability	0.2-0.3
quite high reliability	0.1-0.2
extremely high reliability	0.05-0.1
Next to impossible	0.0-0.05

TABLE A-3

Degrees of Fuzziness

EXPRESSIONS OF FUZZINESS	PARAMETER M
Low fuzziness	2.0
Medium fuzziness	2.5
Rather high fuzziness	3.0
High fuzziness	3.5

For example, the linguistic, "standard reliability", with an initial numerical failure probability estimate of 0.45 with a low degree of fuzziness (m equal to 2.0), results in the failure probability possibility distribution of Figure A-2.

This distribution was suggested by T. Onisawa for several reasons. The distribution allows the possibility of a "1" failure probability for systems with low reliability and allows the possibility of a failure probability of "0" for highly reliable systems [A-9]. Another benefit is

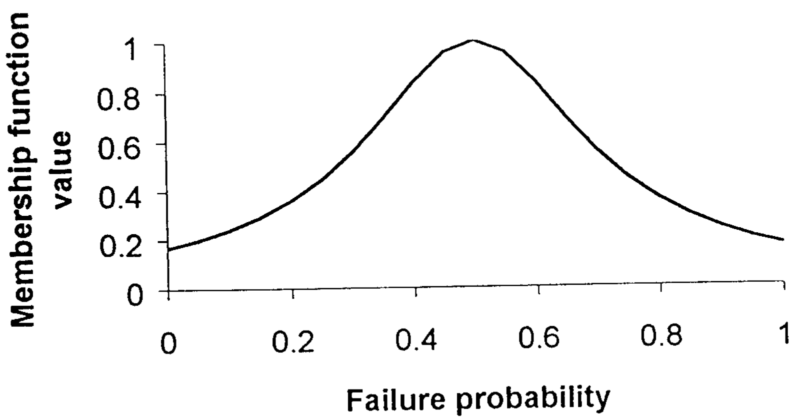


FIGURE A-2. Linguistic failure probability possibility distribution.

quantification of the degree of fuzziness which depicts the certainty in the linguistic value specified.

The arithmetic operations described for fuzzy numbers is complicated considerably when a distribution, like that in Equation 12, is introduced. In order to simplify calculations, the above possibility distribution is converted to a triangular fuzzy number. The linguistic variables are then compatible with the fuzzy numbers developed from data and are easily propagated through a fault tree. The conversion from possibility distribution to triangular fuzzy number is based on the points where the failure probability, x, is equal to "0", "r", "1", and the definition of a line where y is the membership function value (Equation 13). Two lines forming a triangle are constructed between the three points yielding the approximated triangular fuzzy number defined in Equation 14.

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}\left(x - x_1\right) \qquad (13)$$

$$y = \begin{cases} \dfrac{20xr^{m} + r}{r\left(1 + 20r^{m}\right)} & when \quad 0 \le x \le r \end{cases}$$

$$y = 1 \quad when \quad x = 1 \tag{14}$$

$$y = \begin{cases} \dfrac{20(r-1)^{m-1}}{1 + 20(1-r)^{m}}(x - r) + 1 & when \quad r \le x \le 1 \end{cases}$$

As an example, the standard reliability possibility distribution in Figure A-2, with r equal to 0.45 and m equal to 2.0, is converted to a triangular fuzzy number. First, the three points where x is equal to "0", "r", and "1" are determined and shown below.

$$(0, 0.198), (0.45, 1), (1, 0.142) \tag{15}$$

A line is then constructed between the first and second points and the second and third points using Equation 14.

$$y = \begin{cases} \dfrac{20x \bullet (0.45)^{2.0} + 0.45}{0.45 \bullet \left(1 + 20 \bullet (0.45)^{2.0}\right)} & when \quad 0 \le x \le 0.45 \\ 1 \quad when \quad x = 0.45 \\ \dfrac{20 \bullet (0.45 - 1)^{2.0-1}}{1 + 20 \bullet (1 - 0.45)^{2.0}}(x - 0.45) + 1 & when \quad 0.45 \le x \le 1.0 \end{cases} \tag{16}$$

A comparison of the possibility distribution and the approximated triangular fuzzy number developed above is shown in Figure A-3. It can be seen that the spreads and mean values are the same and that only the intermediate membership functions differ slightly. Since only the three defining points are needed for propagation this seems a reasonable approximation.

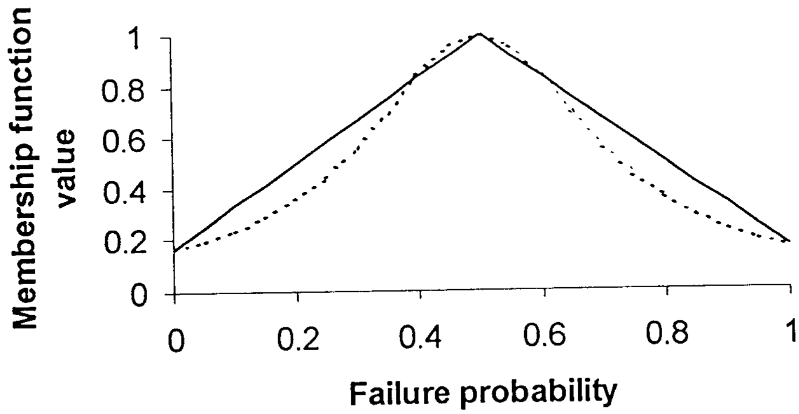


FIGURE A-3. Comparison of possibility distribution and approximated triangular number.

FAULT TREE

A fault tree illustrates the sequence of events, both normal and fault, that may lead to a system failure. Reliabilities of system components and probabilities of certain events can be combined using the fault tree to determine the system's overall reliability. System failure is known as the "top event." The tree is constructed working backward from this event to construct sequences that could lead to the failure. The elements of the tree are the events and logic gates connecting the events.

A logic gate contains one or more input events and one output event. The two most common logic gates are the AND and OR gates. The AND gate requires the occurrence of all the input events to yield the output event. The OR gate output event will occur if any input event occurs. The AND and OR gates use the same logic as components in parallel and series, respectively [A-10].

Several types of events are used to develop a fault tree. Fault events are the output events of a logic gate. The event follows the occurrence of another event. These events are represented graphically by a rectangle. A basic event is an inherent component failure. Basic events cannot be broken down into other events and thus signify the end of the sequence branch. Basic events

appear as circles on fault tree diagrams. Two other types of events should be mentioned, the external event and the undeveloped event. These may or may not be basic events but both act as terminating events in the sequence. The external event is an event that occurs at the predetermined boundary of the system. To further reduce this event would be outside the scope of the analysis. The undeveloped event is one that is not considered due to a lack of information [A-11].

Before constructing the actual fault tree, it is necessary to;

1) Determine the scope of the project.

2) Clearly state all assumptions made in the construction.

Determination of the "top event" helps to define the purpose and scope of the fault tree. The top event should be clearly defined and it may be necessary to modify the definition as succeeding events are established. The scope of the project is limited by the boundaries placed on the system, and the degree of resolution of the analysis. By defining boundaries it becomes clear which components will be considered and which will not. It is also necessary to state to what degree components will be dissected. A component may be broken down into its most elementary components if reliability data exists for the elements.

Any assumptions made in the analysis should be documented for future referencing. Operating conditions and equipment configurations present at the time of the top event should be stated. Any events that are being intentionally neglected such as lightning, wiring failures or design faults, also should be noted [A-10].

After defining the top event it is necessary to determine the events that could directly lead to the top event. Some common failures that should be considered include hardware, software, human errors and failures due to environmental or operational stresses. After determining the events leading to the top event, the process continues downward until all sequences are terminated. This may occur by reaching a basic event, an external event or an undeveloped event.

DESCRIPTION OF A TYPICAL FOAM SUPPRESSION SYSTEM

A simplified system was contrived from the major components of a typical AFFF suppression system. This example system is not a rigorous representation of an actual system, but is intended only to illustrate the engineering application of the theory presented. The system is designed to protect aircraft in hangers from fire. Because of the large wing size on many aircraft it is necessary to have a suppression system for under-wing protection in addition to the typical overhead system. The overhead sprinkler system consists of a pre-action system and sprinkler heads. The under-wing system is composed of eight oscillating monitor nozzles. The two subsystems, the overhead sprinkler system and under-wing system are both supplied by the same foam supply room, with each system having its own riser. The overhead sprinkler system pre-action system riser is equipped with a valve tripped by heat detectors. Schematics of the foam equipment room, pre-action sprinkler system riser and oscillating monitor riser, are seen in Figures A-4, A- 5, and A-6, respectively.

The foam equipment room subsystem shown in Figure A-4 is defined between the foam concentrate storage tank and the 3-inch swing check valves. Other components include a diesel pump, an electric pump, five manual valves and 3-inch piping. The failure of the jockey pump, which only maintains system pressure when the other pumps are not operating, does not contribute to system failure. Manual valve failure is defined to be when a valve fails to remain open. This definition accounts for the many possible causes for the valve to be closed or blocked encountered in the reference data [A-4]. The last component in the foam equipment room whose failure will lead to system failure is piping. The most common type of pipe failure is pipe gasket failure and therefore these failure rates [A-4] are used to calculate pipe rupture probabilities.

The pre-action subsystem shown in Figure A-5, has boundaries at the foam and water inlet piping and the mixture outlet piping. The foam concentrate passes through a pressure proportioner before meeting the water in a ratio controller. The water line contains a manual valve and a pre-action valve with electric solenoid. The mixture leaves the ratio controller passing through a manual valve and an air check valve before reaching the glass-bulb sprinkler.

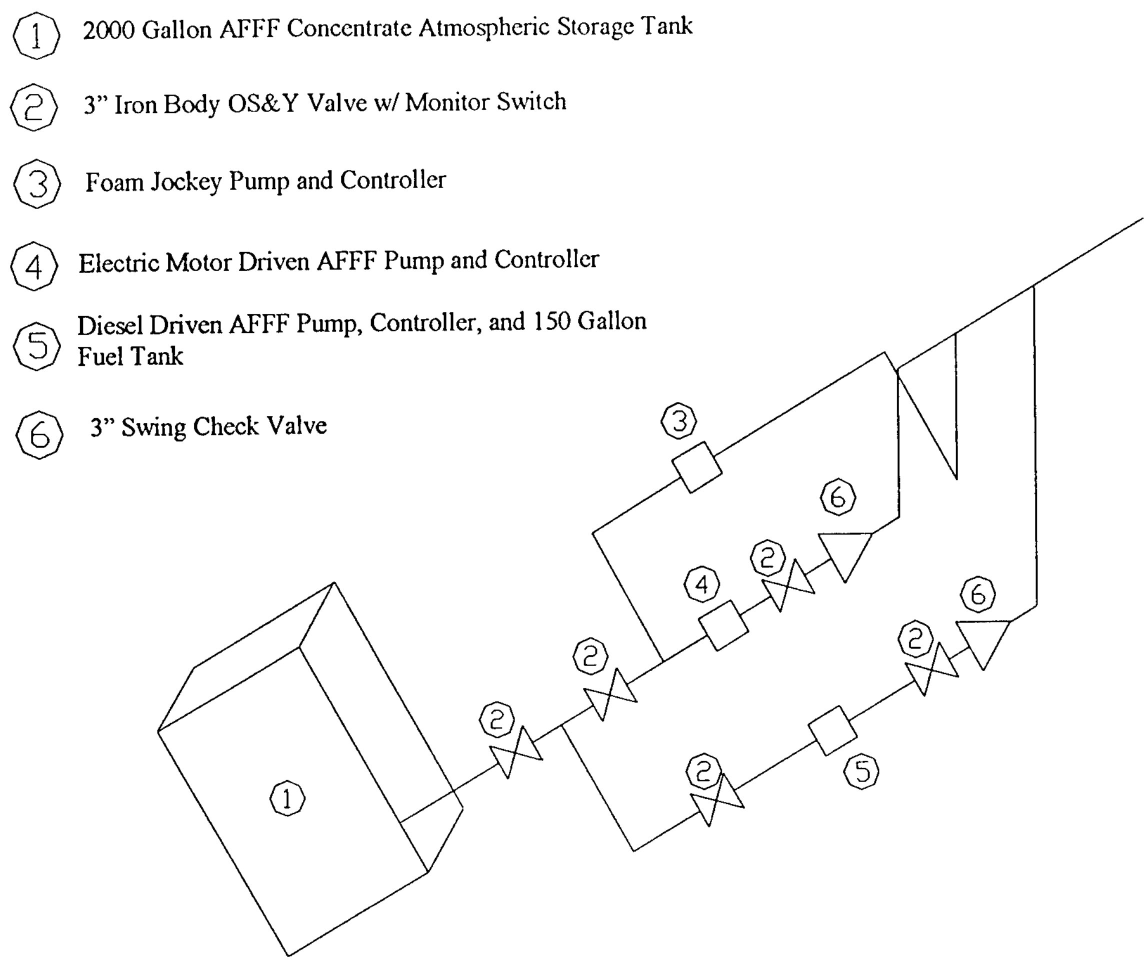


FIGURE A-4. Foam equipment room schematic.

Sprinkler head failure rates were negligible when compared to the failure rates of other components in the system and were therefore neglected in the analysis.

The oscillating monitor nozzle riser shown in Figure A-6, is defined between foam and water inlet piping and the oscillating nozzle. Much like the pre-action riser, foam concentrate passes through a pressure proportioner and enters the ratio controller. The water passes through a manual valve and a deluge valve with electric solenoid before reaching the ratio controller. The mixture is then piped to the oscillating nozzle.

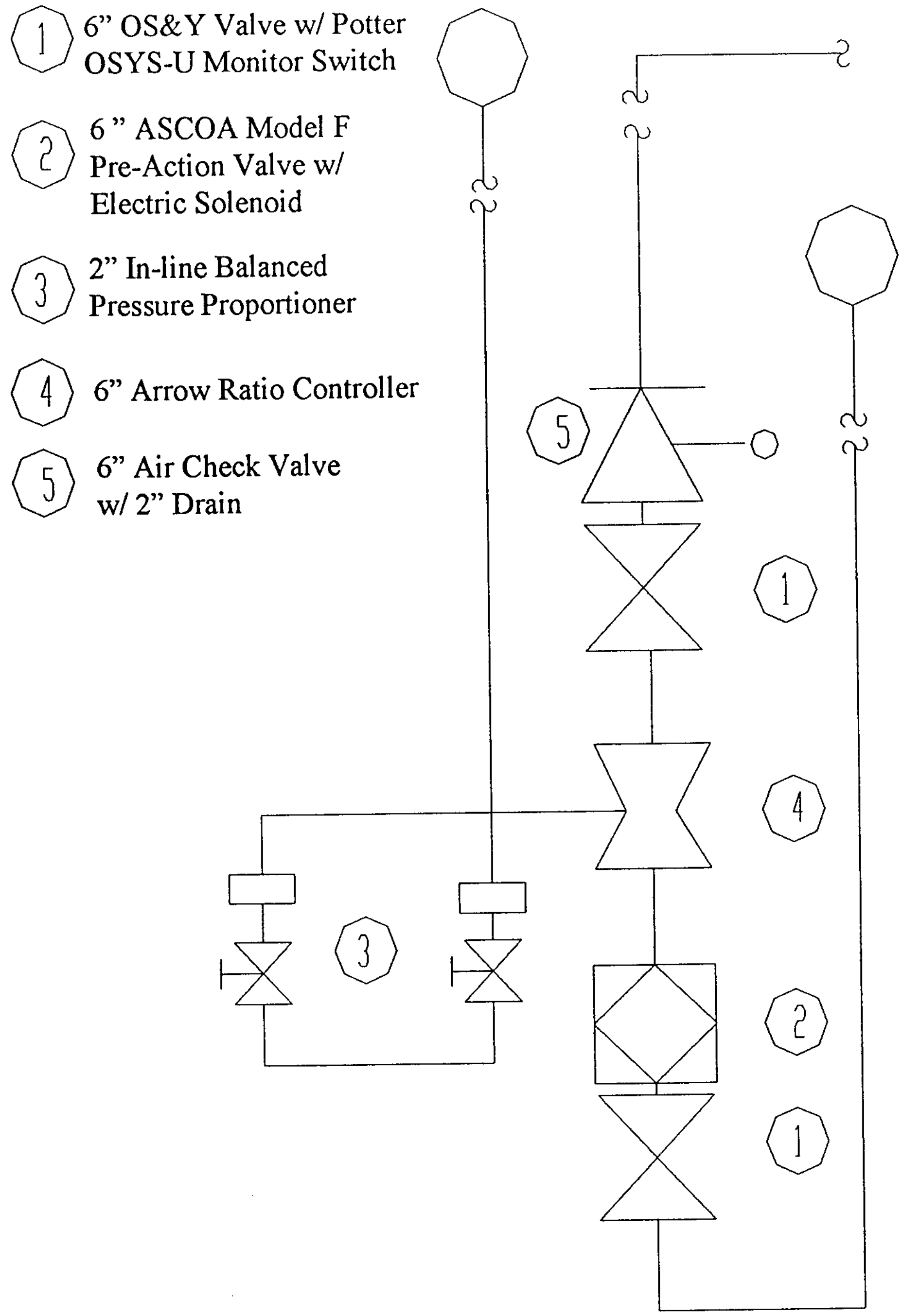
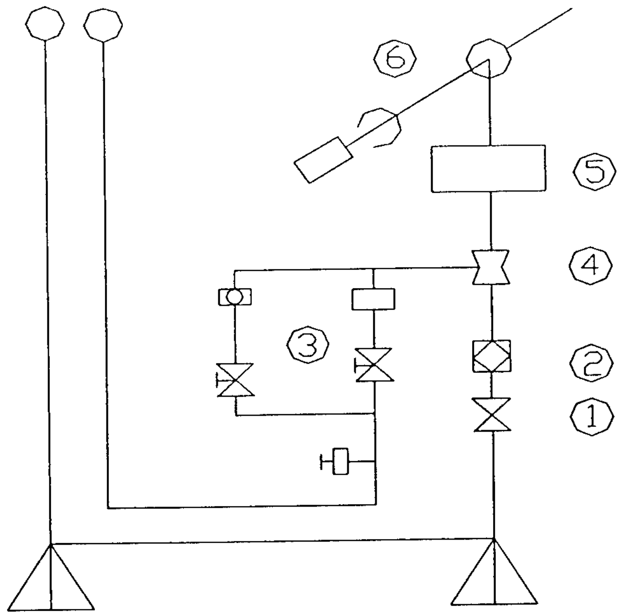


FIGURE A-5. Pre-action riser schematic.



1 4” OS&Y Valve w/ Potter OSYS-U Monitor Switch

2 4” ASCOA Model F Deluge Valve w/ Electric Solenoid

3 1 ½ ” In-line Balanced Pressure Proportioner

4 4” Arrow Ratio Controller

5 Spectrum Model #4 Oscillating Monitor

6 Williams BTM-500 Monitor Nozzle

FIGURE A-6. Oscillating monitor nozzle riser schematic.

Two types of detector devices are primarily used in older, existing systems, heat and UV-IR detectors. A heat detector alarm opens a pre-action valve and allows the system to become charged with a water and AFFF mixture. A UV-IR detector alarm activates two oscillating nozzles. A total of eight detectors and eight oscillating nozzles comprise the under-wing system. UV-IR and heat detector failure rates include device and associated solid-state device failure rates from Lees [A-5].

FOAM SUPPRESSION SYSTEM FAULT TREE

Fault trees were developed and analyzed to determine the reliability of a foam suppression system. These trees were developed to illustrate the methodology and are meant only to provide the framework for a more extensive analysis.

Two failure modes were considered as top events, failed-safe and failed-dangerous. A system is failed-safe if it activates in the absence of the initiating conditions, in this case activation when there is no fire. A system is failed-dangerous if it fails to activate in the presence of the initiating stimuli, a fire. The conditional probability that a system is failed-safe, P_s, or failed-dangerous, P_d, is the probability that it activates in the absence of stimuli, or fails to activate in the presence of stimuli, respectively. The unconditional probability, P_s* and P_d*, is the probability that the system fails-safe or fails-dangerous in an unknown environment. The unconditional probability is calculated using the conditional probability and the demand probability, or probability of stimuli, d [A-3], using equations 17 and 18.

$$P_s^* = P_s * (1 - d) \qquad (17)$$

$$P_d^* = P_d * d \qquad (18)$$

Multiplying the two event probabilities is equivalent to connecting the events with an AND gate and thus may be applied to the fault tree. This yields the unconditional probability of a failed-safe system or a failed-dangerous system as the top event.

The top event of the failed-dangerous fault tree shown in Figure A-7 is the system's failure to control a fire. This combines the probability of a fire and the probability of the system failure. The system can fail if either of it's two subsystems, the sprinkler system or under-wing system, fail. A sprinkler system failure can be defined in three ways. The system may not be charged when a sprinkler is activated, the foam-system may fail to deliver foam when needed, or it may fail to deliver the correct mixture of foam and water. Foam-system failures can also lead to

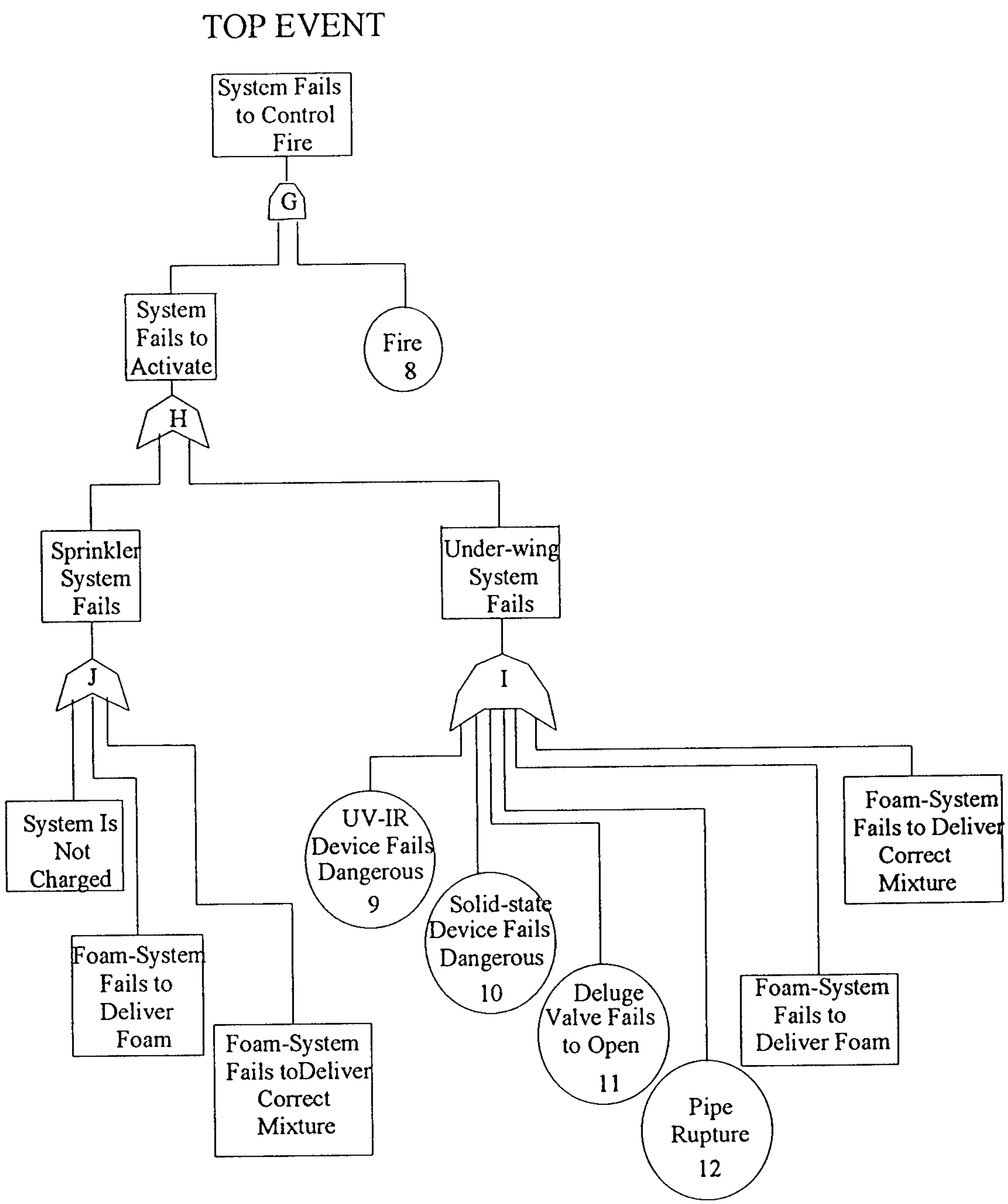


FIGURE A-7. Failed-dangerous fault tree.

failure of the under-wing system. Other possible causes for under-wing system failure include, UV-IR device including solid-state device failed-dangerous, deluge valve failing to open, or pipe rupture.

The events leading to the sprinkler system not being charged are illustrated in FigureA-8. Failure of the pre-action valve or air-check valve to open would lead to this failure. If the manual valve is closed or blocked for any reason, or if a pipe ruptures or is damaged, the system would not be charged. In addition, if a heat detector fails to detect, the pre-action system would not be activated and the system would not be charged.

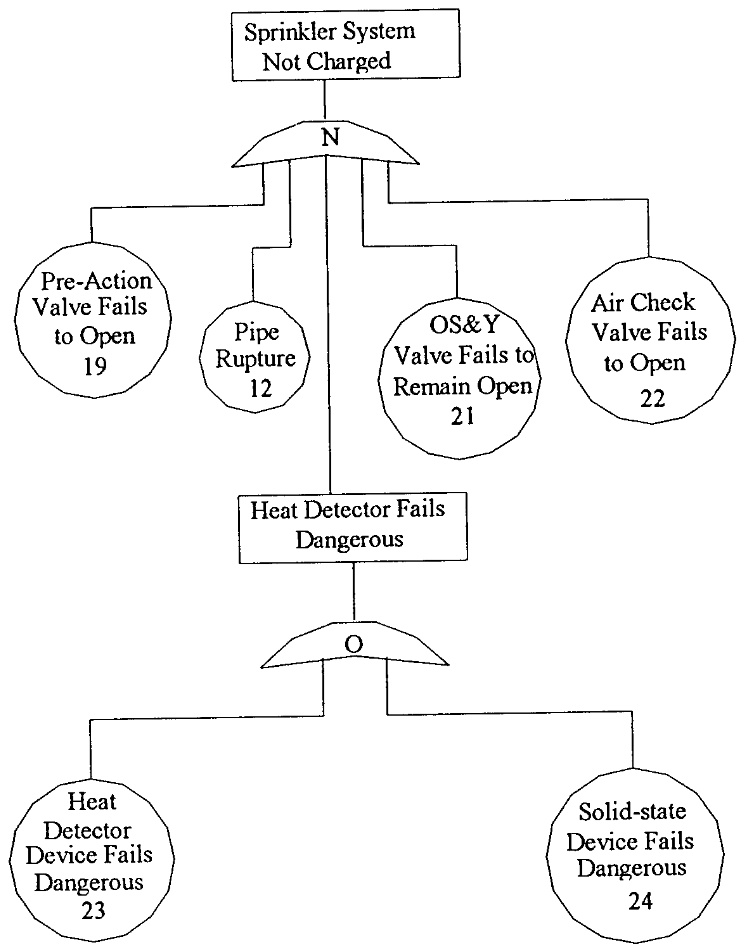


FIGURE A-8. Sprinkler system not charged fault tree.

The foam-system failure to deliver foam could be caused by several events (Figure A-9). A ruptured pipe or failure of a check valve to open in the foam-equipment room would lead to a delivery failure. Failure of both the electric and diesel pump would also result in delivery failure.

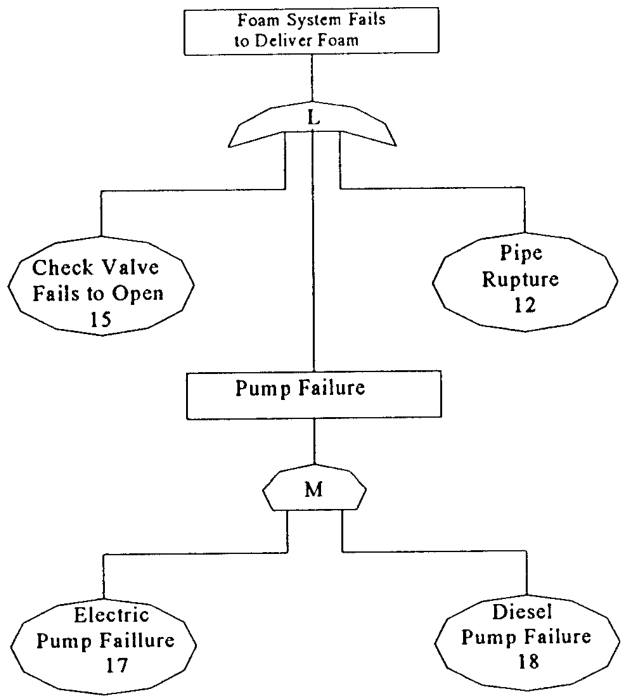


FIGURE A-9. Foam system failure to deliver foam fault tree.

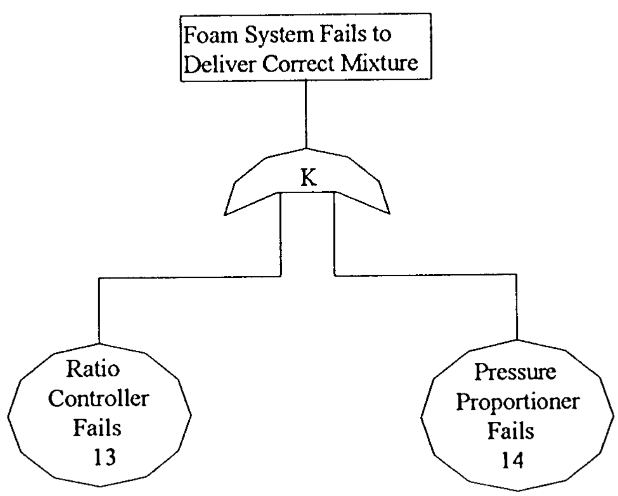


FIGURE A-10. Foam system failure to deliver correct foam-water mixture.

The failure of the foam-system to deliver the correct mixture of foam and water could lead to the systems failure to control a fire. If the pressure proportioner fails low or the ratio controller fails, the mixture will not have the properties necessary to control the fire. If the proportioner fails high, the foam will run out too early, and the fire will not be controlled (Figure A-10).

The failed-safe fault event occurs if the system falsely activates and there is no fire (Figure A-11). The system falsely activates if the under-wing or sprinkler system falsely activates. The sprinkler system will only fail-safe if a sprinkler fails safe and the system falsely charges. The system will only falsely charge if both the air-check valve and pre-action valve fail to open. On the other hand, the under-wing system will fail-safe if one UV-IR detector fails safe or the deluge valve fails to open.

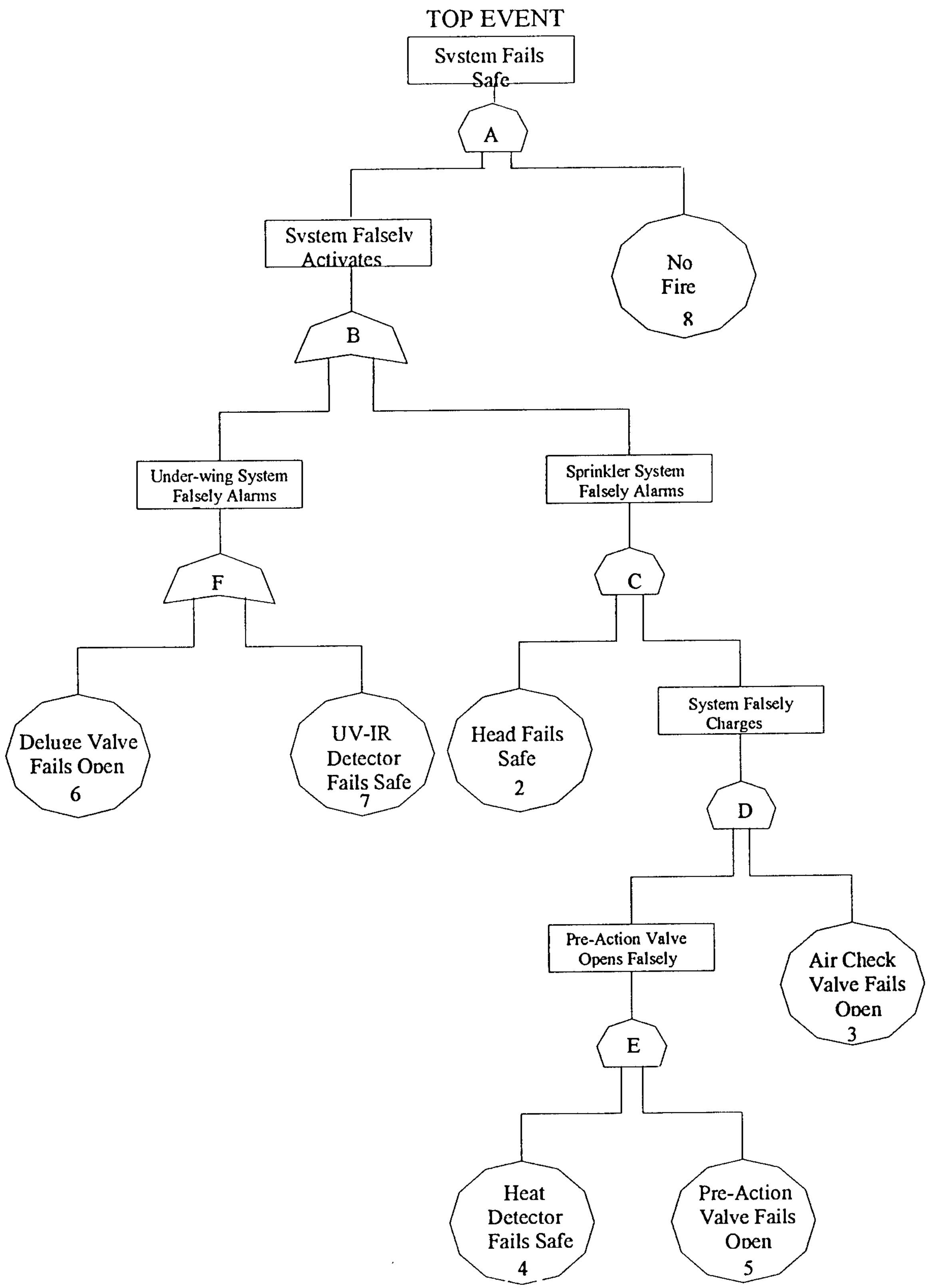


FIGURE A-11. Failed-safe fault tree.

OBTAINING THE MINIMUM CUT SET

The minimum cut set is a sequence with a minimum number of events that can lead to the top event. Determining the minimum cut sets of the fault tree allows the engineer to evaluate weak links in the system design. Top event probabilities generally decrease with the number of events required to reach the top event, therefore minimum cut sets with the fewest number of events are a good starting place for determining weak links. However, a failure requiring only two events may initially be considered a weak link, but the probabilities of these events must also be considered. A failure requiring only two events with one or both having high failure probability may suggest system modifications are needed. Probabilities can also be propagated through minimum cut sets, rather than very large fault trees, to determine system reliability. An algorithm developed by J. Fussell and W. Vesely systematically determines the minimum cut sets [A-10]. The method is based on the premise that AND gates increase the number of events in the cut set and OR gates increase the number of cut sets.

The first step of the algorithm is to label all gates using letters and all terminating events using numbers. The first gate below the top event is written. This gate is then replaced by its inputs. If the gate is an AND gate, the inputs are placed in the same row crossing out the original gate. If the gate is an OR gate, the original gate is replaced in that row by one input and the other inputs are placed below the first row in the column. All other entries in the original row are copied into the columns. This procedure is repeated, crossing out each gate until only terminating events are remaining. The events in each row are then the minimum cut sets. This methodology is illustrated using the failed-safe fault tree for the foam suppression system.

The failed-safe fault tree of Figure A-11 is redrawn in Figure A-12 a with gates and events labeled with letters and numbers, respectively. The algorithm begins by writing the first gate and replacing it by it's inputs. The inputs are placed in a row because A is an AND gate.

~~A~~ B 1

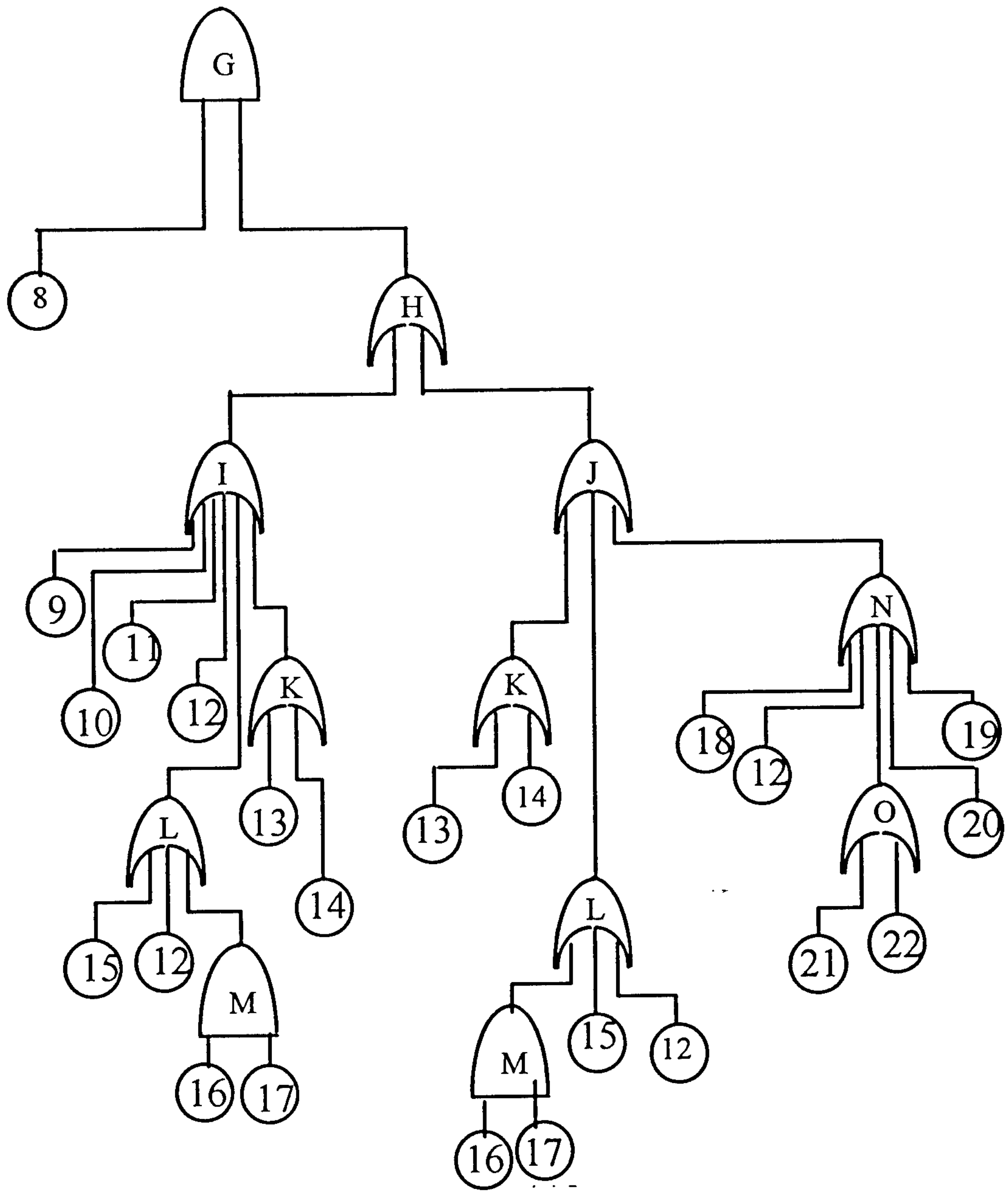


FIGURE A-12a. Failed-Dangerous fault tree for minimum cut set algorithm.

Since gate B is an OR gate, it is crossed out and replaced by one of its inputs, the other is placed in a new row and the "1" is copied into the new row also.

~~A~~ ~~B~~ C 1

F 1

Gate C is an AND gate so it is crossed out and its inputs are placed in the same row. Since F is an OR gate it is replaced by one of its inputs, the other is placed in a new row and the "1" is copied also.

~~A B C~~ D 2 1

~~F~~ 6 1

7 1

The next gate, D is an AND gate and is therefore replaced by its inputs.

~~A B C D~~ E 3 2 1

~~F~~ 6 1

7 1

Gate E is replaced with one of its inputs, the other input is placed in a new row, and the entries from the original row are also placed in the new row. The remaining rows of events are the minimum cut sets.

~~A B C D E~~ 4 3 2 1

~~F~~ 6 1

7 1

5 3 2 1

or;

1, 2, 3, 4

1, 6

1, 7

1, 2, 3, 5

Evaluating the minimum cut sets reveals two sets requiring only two events to lead to the top event. This leads to the initial conclusion that these are the weakest links in the failed-safe fault tree. A UV-IR detector fail-safe or a deluge valve failing open when no fire is present will cause the system to fail-safe. Considering the high probability of no fire and the high probability of a UV-IR detector falsely alarming, this is a significantly weak link in the system.

Applying the minimum cut set algorithm to the failed-dangerous fault tree in Figure A-12b yields the following minimum cut sets.

8,9

8,10

8,11

8,12

8,13

8,14

8,15

8,16,17

8,18

8,19

8,20

8,21

8,22

The number of cut sets containing only two events in the failed-dangerous fault tree initially suggest a significant number of weak links in the system. However, the low probability of a fire yields a very low probability of two of these events occurring. Therefore the weak links in the failed-dangerous fault tree are less consequential than the weak links in the failed-safe fault tree.

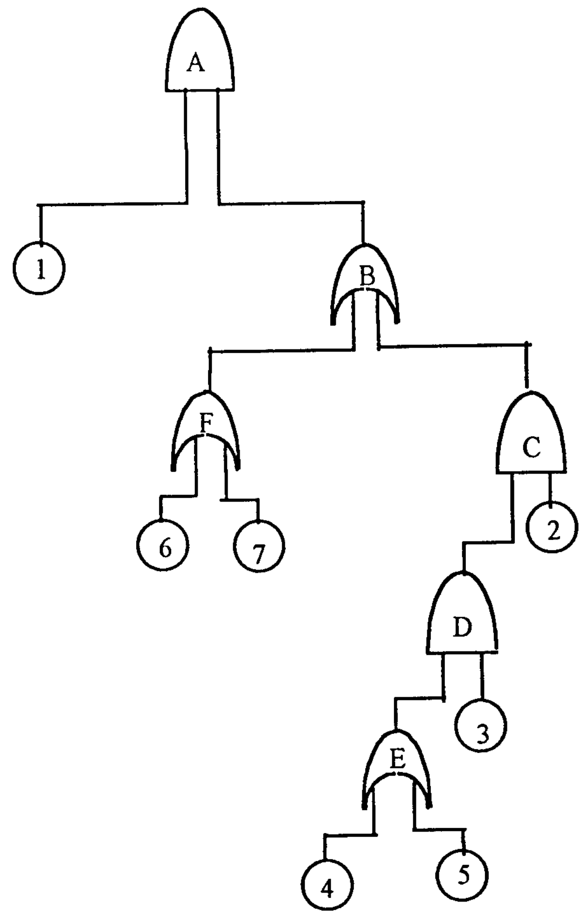


FIGURE A-12b. Failed-safe fault tree for minimum cut set algorithm.

CALCULATING THE RELIABILITY OF THE SYSTEM

The reliability of the system can be calculated using the reliability of components and/or probability of events. Data are most often tabulated in terms of failure rate, which from Equation 7 yields the reliability, R. Since fault trees deal with events, it is most logical to propagate probabilities. Using the fact that failure probability is (1-R), component reliabilities are easily converted to failure probability, and after propagation the top event probability yields system reliability. Starting with the basic events of the minimum cut set (or for smaller trees, all basic events,) the reliability of the fault events or logic gate outputs are calculated based on the

type of gate and the inputs. The probability of the output of an AND gate, (or events in parallel), is found by multiplying the input probabilities P_I, using

$$P_{AND} = \prod_{i=1}^{n} P_i \tag{19}$$

The reliability of the OR gate output, (or events in series), is found by multiplying input reliabilities or the probability is found using Equation 20 [A-10].

$$P_{OR} = 1 - \prod_{i=1}^{n} \left(1 - P_i\right) \tag{20}$$

The above equations can also be used with fuzzy numbers. However, arithmetic operations on fuzzy numbers can be difficult and tedious. An approximation method can be used to greatly simplify the computation. Direct multiplication of triangular fuzzy numbers does not usually lead to a triangular result. However, the approximation yields a triangular fuzzy number with the same defining three points, but with different membership functions for some of the intermediate values.

For triangular fuzzy numbers, the above equations are applied to each of the three points defining the number [A-1] as seen in Equations 21 and 22. The equations are applied to the four points of a trapezoidal number in the same manner [A-2]. Figure A-13 illustrates this principle.

$$P_{PARALLEL} = \left[\prod_{i=1}^{n} a_{1i}, \prod_{i=1}^{n} a_{2i}, \prod_{i=1}^{n} a_{3i} \right] \tag{21}$$

$$P_{SERIES} = \left[1 - \prod_{i=1}^{n} \left(1 - a_{1i}\right), 1 - \prod_{i=1}^{n} \left(1 - a_{2i}\right), 1 - \prod_{i=1}^{n} \left(1 - a_{3i}\right) \right] \tag{22}$$

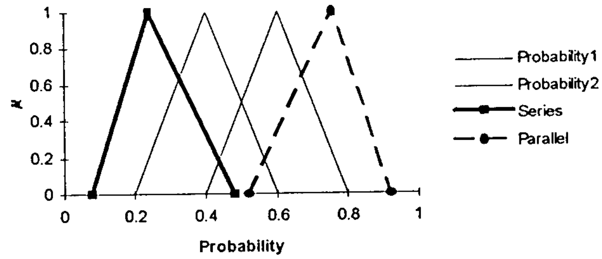


FIGURE A-13. Parallel and series combinations of fuzzy numbers.

The three defining points of most triangular fuzzy numbers have membership function values, μ, of 0, 1, and 0, but the linguistic triangular numbers developed from the distribution in Equation 12 do not extend to the zero membership function value. Because interval arithmetic applies to numbers with equal membership function values, the three defining points of numbers being combined must have equal membership function values. If the two triangular fuzzy numbers below are to be combined in parallel and in series, they must both be defined at the same membership function values.

$$[\ 0/\ 0.4,\ 1/0.5,\ 0/0.6\ ] \tag{23}$$

$$[\ 0.2/\ 0.5,\ 1/\ 0.6,\ 0.2/\ 0.7\ ] \tag{24}$$

This means the first number must be redefined at the points where the membership function values are 0.2 and 1.0 as shown below.

$$[\ 0.2/\ 0.42,\ 1/\ 0.6,\ 0.2/\ 0.58\ ] \tag{25}$$

The numbers are then combined using Equations 21 and 22 for parallel and series combinations, respectively.

$$P_{PARALLES} = \left[(0.5*0.42),(0.6*0.5),(0.7*0.58)\right] \tag{26}$$

$$P_{SERIES} = \left[\ 1-(1-0.5)*(1-0.42),\ 1-(1-0.6)*(1-0.5),\ 1-(1-0.7)*(1-0.58)\ \right] \quad (27)$$

This yields the following new triangular fuzzy numbers.

$$P_{PARALLEL} = [\ 0.2/0.21,\ 1/0.3,\ 0.2/\ 0.41\ ] \quad (28)$$

$$P_{SERIES} = [\ 0.2/\ 0.71,\ 1/\ 0.79,\ 0.2/\ 0.87\ ] \quad (29)$$

RESULTS

The fault tree analysis calculates the probability of failure and thus the overall reliability of the foam suppression system. The fuzzy probabilities of each gate event, for the failed-dangerous scenario, are presented in Table A-4. Using the probability of the top event, a fuzzy reliability, (system operates as designed in the event of a fire) of 0.96 with a lower limit (LL) of 0.90 and an upper limit (UL) of 1, was calculated (Figure A-14). It is important to remember that the UL and LL have membership function values, μ_f, of 0 and that the reported mean has a μ_f of 1. The resulting fuzzy number is a triangle. This illustrates the resulting reliability as having a strong possibility over the entire range. The standard statistical method for determining the reliability of the system does not yield an interval [A-5]. The fuzzy evaluation gives a description of uncertainty as the data spreads are propagated in the fault tree.

The analysis for the failed-safe scenario was computed with a single UV-IR detector which was allowed to trip the system. The high false alarm rate of these detectors is largely responsible for the high-failure probability of 0.59 (LL 0.28, UL 0.96) calculated here. It is this probability that is propagated through the failed-safe fault tree seen in Table A-5.

TABLE A- 4

Fuzzy Probability of Gate Outputs for Failed-Dangerous Fault Tree

Gate	Gate Description	Fuzzy Probability
G	System Fails to Control Fire	(0.00, 0.04, 0.10)
H	System Fails to Operate	(0.21, 0.74, 1.00)
J	Sprinkler System Fails to Operate	(0.16, 0.57, 0.99)
N	Sprinkler System Is Not Charged	(0.10, 0.41, 0.94)
O	Heat Detector Fails	(0.00, 0.04, 0.27)
M	Pump System Fails	(0.01, 0.10, 0.49)
L	Foam Delivery System Fails	(0.02, 0.16, 0.84)
K	Incorrect-Foam Water Mixture	(0.05, 0.15, 0.24)
I	Under-wing System Fails to Operate	(0.07, 0.40, 0.97)

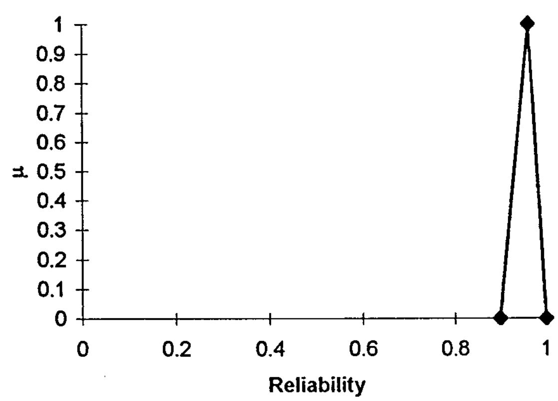


FIGURE A-14. Failed-dangerous reliability.

TABLE A-5

Propagation of Fuzzy Probability in Failed-Safe Fault Tree

Gate	Gate Description	Fuzzy Probability
A	System Fails Safe	(0.28, 0.59, 0.93)
B	System Falsely Activates	(0.31, 0.63, 0.93)
C	Sprinkler System Falsely Activates	(5.55E-09, 1.52E-10, 0.0)
D	Sprinkler System Falsely Charges	(0.000555, 0.000152, 0.0)
E	Pre-action Valve Falsely Opens	(0.0026, 0.0152, 0.0277)
F	Under-wing System Falsely Alarms	(0.31, 0.63, 0.93)

SENSITIVITY

In an effort to increase system reliability, the sensitivity of the system to the performance of components with high failure probabilities must be examined. Components in the AFFF system with failure probabilities significantly higher than others are the pumps, the pre-action valve, and UV-IR detectors.

The high failure probability of the pumps is countered by placing two in parallel. The fuzzy failure probability of the pumps alone is 0.31 (LL 0.08, UL 0.70). However, the fuzzy probability of both pumps failing simultaneously is only 0.10 (LL 0.01, UL 0.49).

The pre-action valve failure probability effect on the system reliability is significant until the probability of fire is considered. As can be seen in Table A-4, the probability that the system is not charged has a mean value of 0.41, but the overall system failure probability is 0.04 because of the low probability of a fire. The lack of system sensitivity to the pre-action failure probability is further shown by the overall system failure probability when the pre-action system is removed. Setting the probability of the system not being charged to zero, increases the median system reliability value by only 0.01.

The remaining component, the UV-IR detectors have the largest impact on system reliability. This can be seen when the system reliability is computed using multiple UV-IR detectors in series (Figure A-15). With a single UV-IR detector the fuzzy probability is 0.59 (LL 0.28, UL 0.93), when two are required to alarm prior to the system being tripped, the failure probability drops to 0.38 (LL 0.17, UL 0.59), when three are required it drops to 0.23 (LL 0.03, UL 0.81). This makes it necessary to compare the cost of the additional detectors to the cost benefit of the increased reliability.

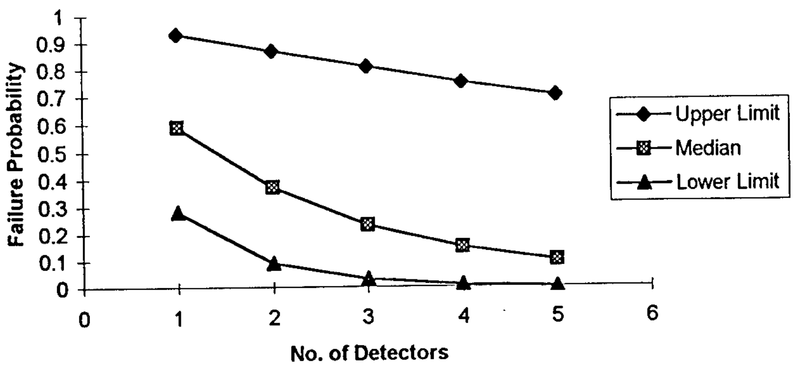


FIGURE A-15. System sensitivity to multiple UV-IR Detectors.

COST BENEFIT ANALYSIS

The cost benefit of increasing system reliability can be found using expected loss as shown in Henley and Kumamoto [3]. The expected loss, I_s, takes into account the cost of a failed-dangerous, C_b, the cost of a failed-safe, C_a, and the probability of each, P_d* and P_s*, respectively. It is then compared to the cost of increased reliability to determine the cost benefit. The equation can also be applied using fuzzy numbers to reflect uncertainty in costs.

$$I_s = C_a P^*_s + C_b P^*_d \qquad (31)$$

Assuming the failed-dangerous and failed-safe costs for this system are the triangular fuzzy numbers seen in Equations 32 and 33, the cost benefit of increasing system reliability is evaluated. Because additional UV-IR detectors greatly increase system reliability the expected loss is calculated for a single UV-IR detector, 2 detectors in series, and 3 detectors in series. These losses are compared with the cost of additional detectors in Figure 16.

$$C_b = (\ 270\text{x}10^6,\ 300\text{x}10^6,\ 330\text{x}10^6\ ) \qquad (32)$$

$$C_a = (\ 2.7\text{x}10^6,\ 3.0\text{x}10^6,\ 3.3\text{x}10^6\ ) \qquad (33)$$

The magnitude of the expected loss for even three detectors in series, versus the total cost of detectors (24 @ approximately $2300 each), illustrates the cost benefit of using multiple detectors.

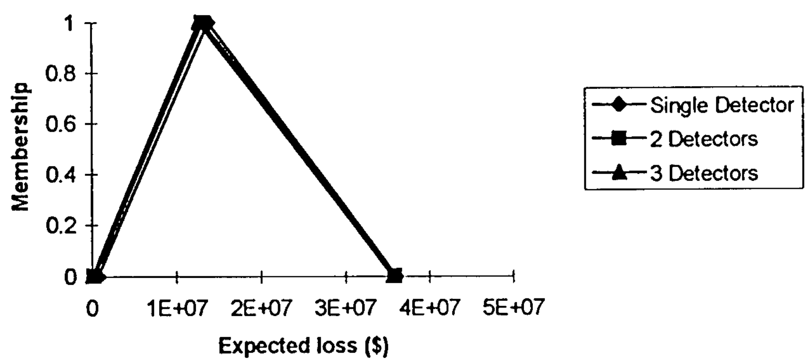


FIGURE A-16. Expected loss using multiple UV-IR Detectors.

CONCLUSION

The methodology proposed in this Appendix can be applied to any fire suppression system. The first step in determining system reliability is to determine component failure rates. The data collected by testing, inspection and maintenance program is an excellent source of information. Additionally, industry and government publications provide sources of failure data. Fuzzy sets can be developed by techniques presented in this paper and applied to specific systems and reliabilities of individual components or applicable subsystems determined. Developing a group of fuzzy sets from available data on system components and using fuzzy possibility theory to define membership functions greatly increases the relevance of a reliability study. The advantage of this method is clear in that expert opinions can be used in a quantitative manner both in the assignment of membership function values form data, and by using linguistic variables.

Once component failure rates have been developed, specific system schematics are used to develop fault trees for individual systems. The failure probability and reliability information that developed form the failure rate data can than be propagated through the actual systems using the

fuzzy arithmetic techniques presented in this Appendix, and overall system reliability will be determined including approximate data spreads. The use of fuzzy arithmetic in fuzzy fault tree analysis greatly increases the frameworks' flexibility for application to various system and system condition. In addition, the results accurately reflect the actual knowledge of the system's reliability and component relationships and allow an analyst to use a wide range of data sources relevant to the system being studied. This fault tree analysis methodology yields a much clearer understanding of the influence of data ranges on the final result. Knowing the triangular shape of the resulting fuzzy numbers provides an easy way to appreciate the uncertainty propagation. The use of the spreadsheet allows many "what if" scenarios to be evaluated quickly in order to develop more reliable designs.

The example system analyzed in this Appendix showed the high probability of UV-IR detectors failing-safe is the primary source of the low failed-safe reliability of the AFFF fire suppression system. The high probability of no fire makes the system very sensitive to component failed-safe probabilities. Adding UV-IR detectors in series increases the system reliability at a low cost when compared to the expected loss of a failed discharge of the system. The system configuration and high component reliabilities leads to the low probability of a failed-dangerous system. The failed-dangerous probabilities for components also have significantly less effect on the system than failed-safe probabilities due to the small probability of fire.

When assigning membership function values to fuzzy reliabilities, a bias can be introduced by a system designer or engineer. This could help to more accurately reflect the environment in which the component will operate, the engineer's experience with the systems performance, and a user's experience with a particular system and operating condition. More significant failures can be reflected in the membership functions and the large data base reflecting many operating environments can still be represented. Information which is qualitative in nature can be used in a quantitative way when the fuzzy set theory is utilized. Trapezoidal fuzzy numbers can represent linguistic values. Both of these areas will be investigated further as to how they can be applied to future analysis of fire protection systems.

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APPENDIX B - CAPITAL COST ESTIMATES FOR CONSTRUCTION OF OLD AND NEW AFFF SYSTEMS

Underwing & Overhead AFFF System (Old System)

AFFF 4 monitor nozzles: Qf = 2,000 gpm; Hangar spklrs = 240 AS Qs = 3,200 gpm; Qtotal = 5,200 (+ 500=5,700)

#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
Hangar Roof Sprinklers						
	6" Wet Alarm Valves	2	ea	$1,000	$2,000	
	6" OS&Y	2	ea	$800	$1,600	
	Alarm switches, supervisory	4	ea	$100	$400	
	Feed main, 6" S-40 (extra)	400	ft	$10	$4,000	
	Seismic Bracing	10	ea	$100	$1,000	
	Sprinklers (at 130ft2/AS +)	240	ea	$10	$2,400	
	Labor installed	240	ea	$62	$14,880	$26,280
#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
Underwing System Piping (4 monitor nozzles, 2 deluge valve zones):						
	6 " Clayton Deluge valve	2	ea	$1,500	$3,000	
	6" OS&Y	2	ea	$800	$1,600	
	4" S-40 pipe	600	ft	$8	$4,800	
	Monitor Nozzles	4	ea	$4,280	$17,120	
	Installation labor pipe	600	ft	$8	$4,800	2 m 100'/day
	Installation, Valves to test	2	ea	$1,600	$3,200	
	Seismic Bracing	10	ft	$100	$1,000	
	Flow switch, abort switch,	2	ea	$100	$200	
	Supervisory, flow switches	2	ea	$200	$400	$36,120
#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
Underwing System Foam Storage and Distribution						
Assumes PDP Pumps, Atmos. Tanks, Volume 1,600 gal tanks redundant, copper pipe to ILBP Proportioners						
	1,600 gallon Atmos.storage tanks	2	ea	$3,750	$7,500	
	PDP pump skids, 60 gpm	2	ea	$26,000	$52,000	
	Inline Balanced Press. Propo'nr 4"	4	ea	$2,754	$11,016	
	Inline Balanced Press. Propo'nr 6"	2	ea	$3,060	$6,120	
	Jockey pump AFFF	1	ea	$5,000	$5,000	
	Brass piping to proportioners	700	ft	$5	$3,500	
	Foam agent to fill first time	1,600	gallons	$15	$24,000	
	Labor to install tanks, pumps	7	m-days	$800	$5,600	
	Labor to install ILBP	8	m-days	$400	$3,200	
	Labor to test	8	m-days	$400	$3,200	
	Mil Spec test foam ILBP	800	gallons	$15	$12,000	
	Optical Detectors	6	ea	$2,800	$16,800	
	Releasing Panel	1	ea	$10,000	$10,000	$159,936
#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
PUMP HOUSE						
Roof demand 3,200 gpm + Floor nozzle demand 2,000 gpm = 5,200 gpm + 500 gpm OHA.						
Supplied by two 250 mm connections to an existing grid.						
	RPP BFP - 2 at 12" outside	2	ea	$20,000	$40,000	
	2,500 at 125	3	ea	$30,000	$90,000	
	150 gpm jockey pump	1	ea	$5,000	$5,000	
	SS Controllers included in above		ea		$0	
	300 mm gate valves	6	ea	$3,000	$18,000	
	300 mm check valves	6	ea	$2,000	$12,000	
	800 mm relief valve	1	ea	$2,000	$2,000	
	Hose test header for 5,000 gpm flow	1	ea	$2,500	$2,500	
	Built in flow measurement	1	ea	$1,000	$1,000	
	250 mm strainers	2	ea	$2,500	$5,000	
	400 mm header in Mech room	30	ft	$50	$1,500	
	Labor to set up, connect	10	man days	$800	$8,000	$185,000
TRENCHING						
	Trenches at 100 ft centers	400	ft	$185	$74,000	$74,185
				TOTAL		$481,521

Underwing AFFF Delivery System (New System)

AFFF nozzles 4 per trench: Qf = 2,000 gpm; Hangar spklrs = 240 AS Qs = 3,200 gpm; Qtotal = 5,200 (+ 500=5,700)

#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
Hangar Roof Sprinklers						
	6" Wet Alarm Valves	2	ea	$1,000	$2,000	
	6" OS&Y	2	ea	$800	$1,600	
	Alarm switches, supervisory	4	ea	$100	$400	
	Feed main, 6" S-40 (extra)	400	ft	$10	$4,000	
	Seismic Bracing	10	ea	$100	$1,000	
	Sprinklers (at 130ft2/AS +)	240	ea	$10	$2,400	
	Labor installed	240	ea	$62	$14,880	$26,280
#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
Underwing System Piping (4 trenches 2 deluge valve zones) : 4 NOZZLES PER TRENCH						
825 gpm	6 " Clayton Deluge valve	2	ea	$1,500	$3,000	
	6" OS&Y	2	ea	$800	$1,600	
	6" S-40 pipe	600	ft	$10	$6,000	
	4" S-40 pipe	400	ft	$8	$3,200	
	Floor nozzles & special plate	16	ea	$500	$8,000	
	Installation labor pipe	1,000	ft	$8	$8,000	2 m 100'/day
	Installation, Valves to test	2	ea	$1,600	$3,200	
	Seismic Bracing	10	ft	$100	$1,000	
	Flow switch, abort switch,	2	ea	$100	$200	
	Supervisory, flow switches	2	ea	$200	$400	$34,600
#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
Underwing System Foam Storage and Distribution						
Assumes PDP Pumps, Atmos. Tanks, Volume 600 gal tanks redundant, copper pipe to ILBP Proportioners						
	600 gallon Atmos.storage tanks	2	ea	$2,300	$4,600	
	PDP pump skids, 60 gpm	2	ea	$20,000	$40,000	
	Inline Balanced Press. Propo'nr	2	ea	$3,060	$6,120	
	Jockey pump AFFF	1	ea	$5,000	$5,000	
	Brass piping to proportioners	400	ft	$5	$2,000	
	Foam agent to fill first time	600	gallons	$15	$9,000	
	Labor to install tanks, pumps	7	m-days	$800	$5,600	
	Labor to install ILBP	8	m-days	$400	$3,200	
	Labor to test	8	m-days	$400	$3,200	
	Mil Spec test foam ILBP	300	gallons	$15	$4,500	
	Optical Detectors	6	ea	$2,800	$16,800	
	Releasing Panel	1	ea	$10,000	$10,000	$110,020
#	ITEM	Quantity	Unit	Unit Cost	Total Cost	Group Cost
PUMP HOUSE						
Roof demand 3,200 gpm + Floor nozzle demand 2,000 gpm = 5,200 gpm + 500 gpm OHA.						
Supplied by two 250 mm connections to an existing grid.						
	RPP BFP - 2 at 12" outside	2	ea	$20,000	$40,000	
	2,500 at 125	3	ea	$30,000	$90,000	
	150 gpm jockey pump	1	ea	$5,000	$5,000	
	SS Controllers included in above		ea		$0	
	300 mm gate valves	6	ea	$3,000	$18,000	
	300 mm check valves	6	ea	$2,000	$12,000	
	800 mm relief valve	1	ea	$2,000	$2,000	
	Hose test header for 5,000 gpm flow	1	ea	$2,500	$2,500	
	Built in flow measurement	1	ea	$1,000	$1,000	
	250 mm strainers	2	ea	$2,500	$5,000	
	400 mm header in Mech room	30	ft	$50	$1,500	
	Labor to set up, connect	10	man days	$800	$8,000	$185,000
TRENCHING						
	Trenches at 50 ft centers	600	ft	$185	$111,000	$111,185
				TOTAL		$467,085